Electrical Machinery

A Study of Principles of Design, Construction and Operation

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CONTENTS

PREFACE

NUMEROUS requests from the readers of POWER PLANT ENGINEERING for a book embodying the series of articles recently appearing in that publication under the title "A Study of Dynamo Electric Machinery," have prompted the author to compile this and other material prepared by him in the form herewith presented. Only the most generally accepted theories regarding the principles of operation of electric machinery are employed and in offering these, attempt has been made to eliminate the use of the higher mathematics as far as possible. This, together with the inductive method of treatment used should, it is hoped, render the text readily understandable alike to both beginner and advanced student. For purpose of review and to set forth the most important and salient points treated in the text, each chapter has been concluded with a set of questions and practical problems.

In the preparation of the original manuscripts, numerous authoritative sources of information have been freely consulted and where, in the opinion of the author, other writers have used commendable methods for the treatment of the theory of special pieces of apparatus, their method has been employed. This has in particular been the case in the presentation of the theory of the contact maker and oscillograph as used for the determination of current and electromotive force waves and that of the rotary converter, original discussions of which appear in Franklin & Estey's Elements of Electrical Engineering and to which credit is hereby given. In addition, acknowledgement is made for data, wiring diagrams and illustrations taken from such publications as

Power Plant Engineering, The Electric Journal, Electrical Review, Electrical World, Standard Handbook for Electrical Engineers, instruction papers of The Fort Wayne Electrical Correspondence Schools, Croft's Direct-Current Machinery and the catalogues and bulletins of the Westinghouse Electric and Mfg. Co., and General Electric Co.

The author is particularly indebted to Arthur L. Rice, Managing Editor of POWER PLANT ENGINEERING, for numerous valuable suggestions made during the course of preparation of the text, the correction of the manuscript and the reading of proof.

O. H. HENSCHEL.

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CHAPTER I

GENERATING ELECTROMOTIVE FORCE

UNITS OF CURRENT AND ELECTROMOTIVE FORCE; CREATION OF ELECTROMOTIVE FORCE; FACTORS INVOLVED

FLOW of electricity is referred to as electric current, the unit of measurement of which is the ampere, ordinarily designated by the letter I and defined as "the practical equivalent of the unvarying current which, when passed through a solution of nitrate of silver in water, in accordance to standard specifications, deposits silver at the rate of 0.001,118 gram per second." It is the current that will flow through a conductor having a resistance of 1 ohm, that is the resistance at a temperature of 0 deg. C. (32 deg. F.) of a column of mercury 3½ ft. long and having a cross-sectional area of 0.0015 sq. in., and a difference of potential of 1 volt between its ends. The instrument ordinarily used for the measurement of current flow is the ammeter.

As in the case of water, or in fact any fluid, circulation or flow of electricity, can only be established and maintained by the application of a force or a pressure which, in the parlance of electrical engineering, is generally referred to as electromotive force or voltage, and ordinarily designated by the letter E. The unit of such electromotive force is the volt, that intensity of pressure, which, when steadily applied to a conductor having a resistance of 1 ohm, will establish and maintain a flow of 1 amp. of current.

In practically all commercial work, the instrument employed for the measurement of voltage is the voltmeter; for the finer degrees of measurement the millivoltmeter is used.

From the above statements, relative to the values of unit current and unit electromotive force, it is evident that a definite relation must exist between the resistance of a conductor, the current flowing through

it and the applied voltage. This relationship (Ohm's law) is that the current flow in amperes is equal to the electromotive force in volts, divided by the resistance in ohms, which, if we represent the current flow by I,

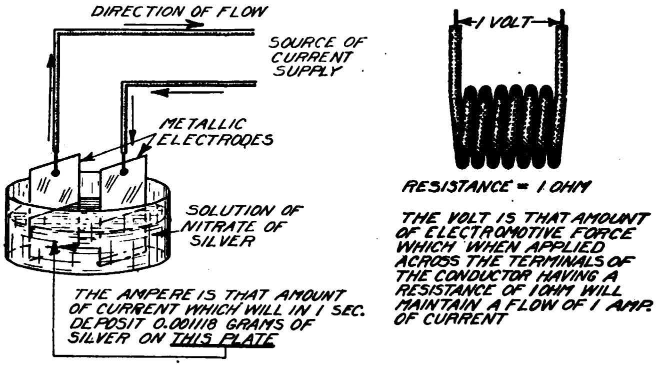


FIG. 1. ILLUSTRATING MEANS EMPLOYED IN DETERMINATION OF UNIT CURRENT AND UNIT ELECTROMOTIVE FORCE

the electromotive force by E, and the resistance by R, may be expressed by this formula:

$$I = E \div R.$$

Or, transposing we may have

$$E = I \times R$$

and $$R = E \div I$$

if knowing the value of the electromotive force and current we desire to solve for R.

Power

IN ELECTRICAL ENGINEERING the unit of power is the watt, the rate at which work is done when a current flow of 1 amp. is maintained under an electromotive force of 1 volt. Numerically power in watts is equivalent to the product of the instantaneous values of electromotive force and current, and generally for sake of convenience is expressed in kilowatts (1000 watts). If, therefore, we let W represent the number of watts and E and I respectively the values of the electromotive force and current, we have, $W = E \times I$ or, with W' representing kilowatts, $W' = (E \times I) \div 1000$.

Seven hundred and forty-six watts are equivalent to one electrical horsepower.

Creation of Electromotive Force

Generation of electromotive force may be accomplished by means of thermocouples, by chemical reactions in batteries or by electromagnetic induction, the principle underlying the operation of all dynamo electric machinery.

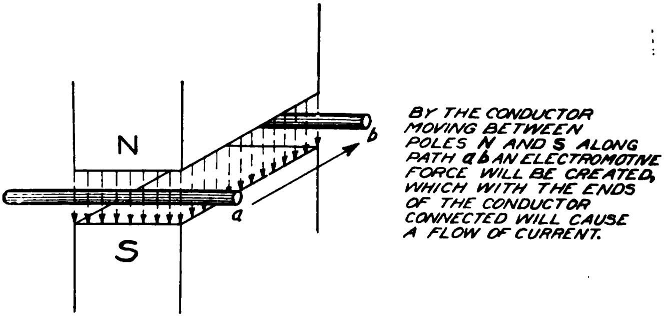


FIG. 2. HOW ELECTROMOTIVE FORCES ARE CREATED

If by means of the hand an electric conductor is, as shown in Fig. 2, caused to move perpendicular to a magnetic field, that is, caused to "cut" or "shear" the magnetic lines of force* emanating from one of the poles of a magnet, a difference of electric potential will be made to exist across the terminals of the conductor. Employing the arrangement shown in Fig. 3, whereby the conductor is made to pass across the magnetic field between the poles N and S, but by means of the slotted insulated metallic upright guides A A carried in its downward movement to be in electrical contact with voltmeter V, this difference of potential will, due to the completed electric circuit, establish a momentary flow of current, as indicated by the deflection of the instrument needle.

Intensity of electromotive force or value of voltage thus created, is dependent upon three factors, the

* The magnetic line of force, the unit of magnetic flux or quantity of magnetism will be defined and discussed later.

strength of the magnetic field, the number of conductors cutting this field and the velocity of travel of the conductor or conductors. Varying anyone or all of these factors will result in a proportionate variation of the electromotive force.

Knowing the direction of travel of the conductor and the direction of the magnetic lines of force, the direction of the electromotive force may be readily

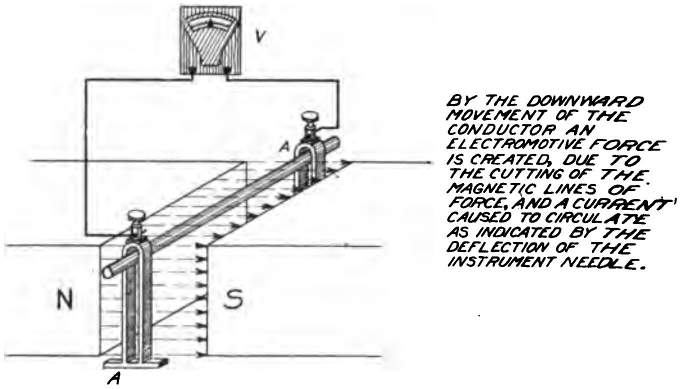


FIG. 3. METHOD EMPLOYED TO DEMONSTRATE PRINCIPLE OF ELECTROMAGNETIC INDUCTION

determined by the application of Fleming's rule. Extend the thumb, the first finger and the middle finger of the right hand so as to bring them at right angles to one another. Then, with the hand held in a position causing the thumb to point in the direction of motion of the conductor, and the first finger in the direction of the magnetic flux, the middle finger will point in the direction of the induced electromotive force.

The principle of this is illustrated in Fig. 4.

The Elementary Generator

PRACTICAL application of the principles of electromagnetic induction, may perhaps, be more readily understood from a study of the elementary electric generator. Shown in Fig. 5, are the two poles, N and S, of a magnet so arranged and with faces of such form as

to allow revolving between them, a coil CC′ mounted on shaft Sh and connected as indicated to two collector rings R R, also carried by shaft Sh. Bearing upon each of the collector rings, are brushes B and B joined by suitable conductors to voltmeter V.

With shaft Sh set in rotation, coil CC′ will revolve, and in doing so, will cut or shear the magnetic lines of force, passing from pole N to pole S, thereby creating an electromotive force, which will vary in degree of intensity and direction, according to the rate of rotation (or the rate at which the magnetic lines of force are being cut) and the direction of rotation of the con-

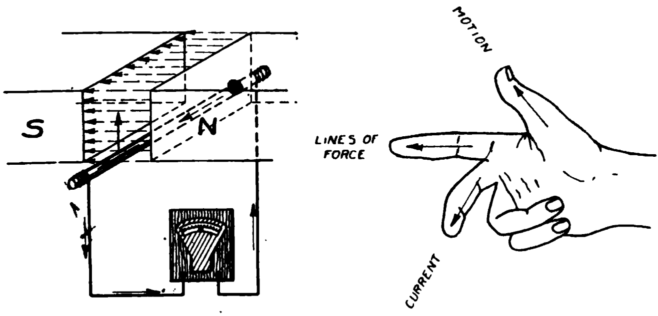


FIG. 4. APPLICATION OF FLEMING'S RULE

ductors with reference to the direction of the magnetic lines of force.

When the plane of the coil is nearly vertical, no magnetic lines of force are being cut, and as a consequence, no electromotive force is induced. However, as the plane of conductors C and C′ passes out of the vertical, magnetic flux is encountered, which in relation to the position of the conductors, increases in intensity until a horizontal position is reached where the maximum number of lines of force are being cut and a corresponding maximum electromotive force created. Further rotation of the coil brings conductors C and C′ through a decreasing magnetic field, which in turn results in a decreasing electromotive force.

After again passing through the vertical plane, the conductors encounter an increasing magnetic field, and

while the resulting electromotive force as before, first increases and then decreases in intensity, the direction of this electromotive force, due to the change in direction of motion of the conductor relative to the direction of the magnetic lines of force is changed.

Connecting voltmeter V as shown, and plotting the readings of this instrument as the coil revolves, will provide a curve similar to that produced in Fig. 5. With the conductors leaving the vertical plane, the

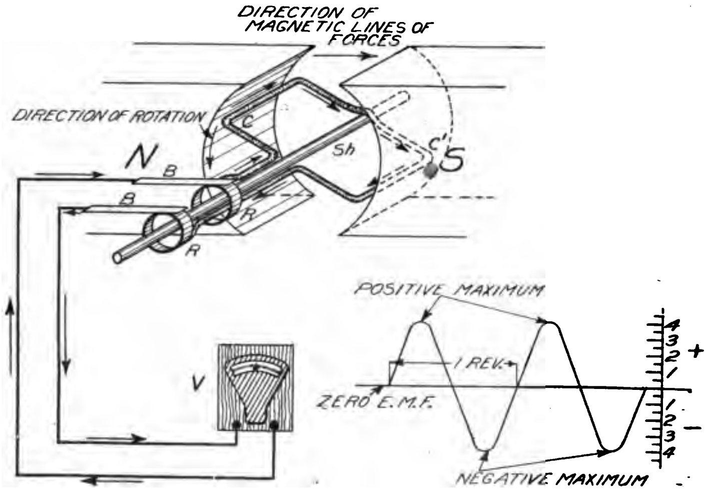


FIG. 5. THE ELEMENTARY ELECTRIC GENERATOR

electromotive force will gradually rise until the maximum magnetic flux is being cut, when the electromotive force will reach a maximum value and decrease as the coil again moves towards the vertical plane. Upon reaching this, the electromotive force will again be zero, only, however, to increase, but in the opposite direction, as the coil continues to move toward the other horizontal plane, after which the electromotive force will decrease assuming a zero value upon reaching the vertical plane.

This explains the principle of operation of the electric generator and particularly of the alternating-current machine.

Calculation of Electromotive Force

When an electric conductor moves across a magnetic field at such a rate as to cut 100,000,000 lines of force per second it will have induced within it an electromotive force of 1 volt. If, therefore, two conductors connected in series are caused to cut 200,000,000 magnetic lines of force per second, or if four conductors connected in series, cut 100,000,000 lines per second, the induced electromotive force will in each case, equal 4 volts.

With E representing the value of the average number of volts induced, F the total number of magnetic lines of force in the field, Z the number of conductors in series and N the number of revolutions made per minute by each conductor, the value of E may be determined by the following formula:

$$E = F\,Z\,N \div (100{,}000{,}000 \times 60)$$

Questions on Chapter I

1. What is the ampere?
2. How is it defined?
3. How is it related to the volt and the ohm?
4. What instrument is used to measure current? What to measure voltage?
5. What is Ohm's law?
6. What is the unit for electric power? What is the name for 1000 times that unit?
7. What is the electric equivalent of 1 hp.?
8. How is electromotive force created?
9. On what three things does the voltage depend?
10. What is Flemings' rule for electromagnetic action?
11. At what position of a coil does it generate the highest voltage?
12. How will voltage from a coil revolving in a magnetic field vary?
13. What rate of cutting magnetic lines will give 1 volt?
14. If an armature has 500 conductors in series and revolves in a field containing 5,000,000 magnetic lines at 300 r.p.m., what voltage will be generated? (125 v.)

CHAPTER II

CREATING THE MAGNETIC FIELD

The Field Structure; Definition of Magnetic Units

EXCEPT for numerous minor fittings, the ordinary direct-current dynamo consists essentially of a stationary member known as the field structure and a revolving element, the armature. Since the advent of the first machine many forms of field structure have been employed; but today the ring type of frame with inwardly projecting pole pieces, such as shown in Fig. 6, is used almost exclusively. Frames and magnet cores are generally made of soft iron or steel, although in the

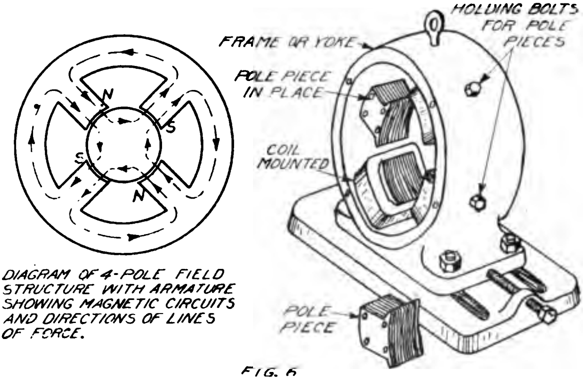


FIG. 6. COMMON FORM OF FIELD STRUCTURE WITH INWARDLY PROJECTING POLE PIECES

larger machines laminated iron pole pieces, secured to the frame by means of suitable stud bolts, are employed. Shoes are fitted to these poles to provide a minimum air gap between pole pieces and armature, to insure a more effective distribution of the magnetic flux and to serve as a means of securing the field coils.

Magnetic Units

As THE AMPERE is the unit of electric current, so is the line of force the unit of magnetic flux. It is an

arbitrary value, being defined as that amount of flux, which, when cut or sheared by a conductor within 1 sec. of time, will induce within that conductor an electromotive force of 1/100,000,000 volt.

To create and maintain a magnetic flux, however, a magnetomotive force analogous to electromotive force or voltage in an electric circuit is required, and as the flow of current in any electric circuit is opposed, or resisted, by the resistance of the conductor, so is the flux or the lines of force in a magnetic circuit resisted by the reluctance of that circuit. The relation between flux or lines of force, magnetomotive force and reluctance is similar to the relation between current, electromotive force and resistance as expressed by Ohm's law. We then have

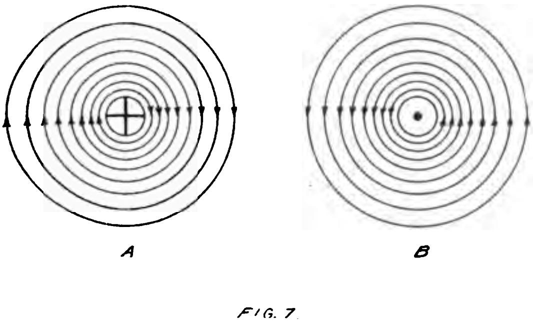


FIG. 7. DIRECTIONS OF LINES OF FORCE SURROUNDING CONDUCTORS CARRYING AN ELECTRIC CURRENT

magnetomotive force equal to the product of flux and reluctance, or flux equal to magnetomotive force divided by reluctance.

When carrying an electric current, a conductor is surrounded by a magnetic field, the strength of which is dependent upon the current flow with the direction of the lines of force dependent upon the direction of current flow. If, as at (A), Fig. 7, we allow the inner circle to represent the section of a conductor with the current passing downward through the plane of the paper, as indicated by the cross or the tail of an arrow, the direction of the flux or lines of force will be clockwise, while

if the flow of current is in the opposite direction, or upward from the plane of the paper, as at B, the lines of force will travel in a counter-clockwise direction.

By wrapping such a conductor around a cylindrical piece of magnetic material, such as soft iron or steel, preventing electrical contact between the two, the lines of force encircling the conductor will induce within the piece of iron or steel—the core— a magnetomotive force, which in turn will establish a flux in the manner indicated in Fig. 8. The degree of magnetomotive force

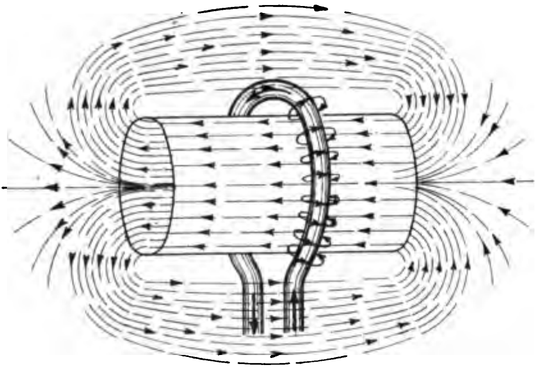


FIG.8

FIG. 8. BY PLACING AN IRON CORE WITHIN A LOOP OF WIRE CARRYING AN ELECTRIC CURRENT MAGNETIC INDUCTION WILL BE SET UP IN THIS MANNER

thus created is dependent upon the product of the number of amperes of current flow through the conductor and the number of turns or times the conductor is wrapped around the core, or, in other words, the number of ampere-turns. If the conductor is wrapped about the core 5 times and carries 20 amp. of current, the number of ampere-turns is equal to 100, although this same number of ampere-turns is obtained when the conductor is wrapped about the core but twice and carries 50 amp., or if 10 turns are employed and a current flow of 10 amp. maintained. In each case the product, or number of ampere-turns is 100.

The practical unit of magnetomotive force is the am-

pere-turn and the force may be represented by the following formula:

$$M = I \times T$$

where M is the magnetomotive force in ampere-turns, I is the current flow in amperes, and T the number of times the conductor is wrapped about the core.

When a magnetomotive force of 1 ampere-turn produces in a magnetic circuit a flux of 1 line, the magnetic circuit in which this is produced is said to have a reluctance of 1 rel, which is equivalent to the reluctance of a prism of non-magnetic material having a length of 3.19 in. and a sectional area of 1 sq. in. The rel is represented by the letter R.

Another property of magnetic circuits requiring consideration is permeance, the reciprocal of reluctance and properly defined as the ease or readiness with which flux may be developed. The unit of permeance is the perm and is represented by P or $1 \div R$.

Substituting permeance for reluctance in expressing the relation between magnetic flux, magnetomotive force and reluctance we have:

Flux = Permeance × Magnetomotive Force.
Permeance = Flux ÷ Magnetomotive Force.
Magnetomotive Force = Flux ÷ Permeance.

Magnetizing Force

In an electric circuit consisting of a conductor of uniform sectional area a drop of electromotive force occurs, which for convenience may be expressed as so many volts drop per 100 ft., or, if so desired, per foot. Similarly in a magnetic circuit a drop of magnetomotive force takes place. This drop, referred to as the magnetomotive force gradient, or magnetizing force, and represented by the letter H, may be defined as a quantity indicating the magnetomotive force expended per unit length of the magnetic path.

The unit of magnetomotive force is, as we have learned, the ampere-turn, the symbol of which is the letter M. If, therefore, we have a magnetic path of length l, the value of the magnetomotive force gradient, the magnetizing force or H, may be readily determined by

dividing M by l. Transposing this equation, we may solve for M or l, the former being equal to the product H and l, while l is equal to M divided by H.

As equations: $H = M/l$; $M = Hl$; $l = M/H$.

On an iron core, having a length of 20 in., and as shown in Fig. 9, is wound a coil, consisting of 1000 turns

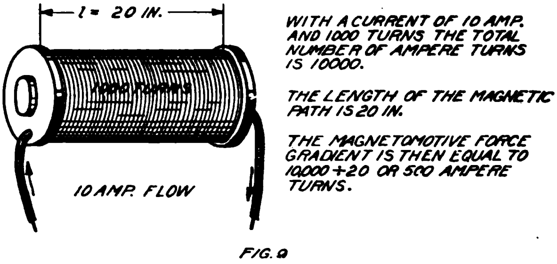


FIG. 9. MAGNETIZING FORCE IS EQUAL TO THE AMPERE TURNS DIVIDED BY THE LENGTH OF THE MAGNETIC PATH

through which an unvarying current of 10 amp. is caused to flow. The total number of ampere-turns, M, is equal to the product of the number of amperes flow, 10, and the number of turns, 1000, or 10,000. $M = I \times T = 10 \times 1000 = 10{,}000$.

The length of this core is 20 in., so that the value of H or the magnetomotive force gradient may be obtained by dividing the total number of ampere turns M or 10,000 by the length l or 20 in., giving as a quotient 500 ampere-turns per inch length. $H = M/l = 10{,}000/20 = 500$.

Flux Density

For sake of convenience the direction of lines of force is always assumed to be from the north pole to the south pole of a magnet. If, therefore, as in Fig. 10, it would be possible to place within the space between the north and south poles a magnetic insulator or shield having an opening 1 in. square and capable of cutting off all of the magnetic lines of force tending to pass from the north pole to the south pole, except those passing through that opening, we would create a path

for these lines of force having a sectional area of 1 sq. in. The number of lines of force passing through this opening would then be referred to as the flux density, the symbol of which is the letter B.

Knowing the value of the total number of lines of force, F, the flux density or B may then be obtained

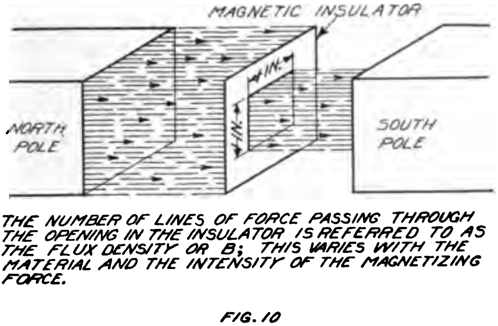


FIG. 10. AN EXAMPLE OF FLUX DENSITY

by dividing this by the sectional area of the magnetic. path A in square inches, or B is equal to F divided by A. Transposing, we may obtain the value of F by the multiplication of B by A or, if the value of A is desired, divide F by B. $B = F/A$; $F = BA$; $A = F/B$.

Permeability and Reluctivity

Magnetic permeability represented by the letter u expresses the ratio of the magnetic flux density to the magnetizing force, or $u = B/H$. Permeability is generally called specific permeance. For non-magnetic materials its value is 3.19.

Reluctivity is the reciprocal of permeability and is represented by v; it is specific reluctance. Unit reluctivity is that through which unit magnetizing force will establish unit flux density.

Magnetic Saturation

Just as a sponge will absorb but a given amount of water, so is it possible for all practical purposes to pro-

duce but a limited flux density or number of lines of force per square inch section of magnetic circuit. Up to a given point called the magnetic saturation point increase of flux density for various materials varies with the magnetizing force H in the manner indicated in Fig. 11. Beyond this point, however, the curves approach the horizontal so that the comparative increase in

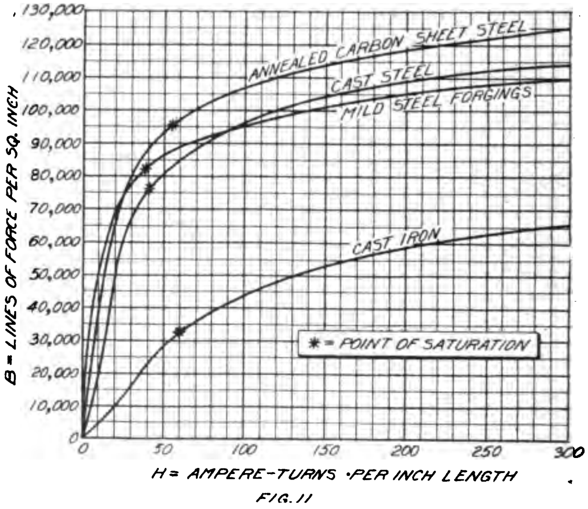


FIG. 11. MAGNETIZING CURVES FOR VARIOUS MAGNETIC MATERIAL

flux density does not warrent the expenditure of the magnetizing force required to produce it. We note from these curves that the point of magnetic saturation for cast iron is about 32,500 lines per square inch; for cast steel it is approximately 77,000 lines, and for mild steel forgings and annealed carbon sheet steel about 83,000 and 95,000 lines per square inch, respectively.

Questions on Chapter II

1. What are the two main elements of a dynamo?
2. What is the most common type of frame?
3. What material is used for field poles? How fastened to the frame?

4. What is the unit of magnetic flux? weber
5. How is the flux produced?
6. State the equivalent of Ohm's law for the magnetic field.
7. What is the relation of current and the magnetic field surrounding it?
8. What are the parts of an electro-magnet?
9. What determines the strength of magnetomotive force? What is the unit?
10. What is reluctance? What is the unit?
11. What in the electric circuit corresponds to reluctance in the magnetic circuit?
12. How is permeance related to reluctance?
13. The reciprocal of resistance is called conductance. Write the equations between electromotive force, current and conductance.
14. Define magnetizing force. How is it related to magnetomotive force?
15. A cast-iron ring 30 in. long has a coil of 500 turns surrounding it. If a current of 6 amperes flows, what are the values of M and H? From Fig. 11, what is the value of B? What is the value of u? If the coil has an area of 2 sq. in., what is the value of F? $M = 3000$ a.t. $H = 100$ a.t. $B = 44{,}000$ $u = 400$. $F = 88{,}000$.
16. If a coil of 200 conductors was revolved in the field of question 15 at a speed of 1000 r.p.m., what E.M.F. would be generated? (2.9 volts.)
17. What is reluctivity?
18. Explain magnetic saturation.
19. What is the permeability of air? Has air a point of magnetic saturation?

CHAPTER III

MAGNETIC CIRCUITS

CALCULATION OF MAGNETIC QUANTITIES AND MAGNET WINDINGS

FIGURE 12 shows a table of the magnetic properties of iron and steel. Knowing the value of B, the required or desired flux density in lines per square inch, it is readily possible to learn the corresponding value of H or magnetomotive force in ampere-turns per inch length.

Carbon sheet steel (annealed)				Cast steel			
B	H	u	u_r	B	H	u	u_r
10,000	5.01	1,996.0	625	10,000	5.64	1,774.0	556.0
20,000	7.20	2,775.0	870	20,000	8.77	2,278.0	714.0
30,000	8.77	3,416.0	1,071	30,000	10.90	2,791.0	875.0
40,000	10.30	3,866.0	1,212	40,000	13.40	2,967.0	930.0
50,000	13.20	3,796.0	1,190	50,000	16.90	2,954.0	926.0
60,000	16.60	3,611.0	1,132	60,000	22.50	2,657.0	833.0
65,000	19.00	3,420.0	.....	65,000	26.00	2,500.0	797.0
70,000	21.30	3,283.0	1,029	70,000	31.00	2,255.0	707.0
80,000	29.40	2,715.0	851	80,000	45.70	1,745.0	547.0
90,000	43.20	2,080.0	652	90,000	70.50	1,276.0	400.0
100,000	67.00	1,490.0	467	100,000	117.40	851.7	267.0
110,000	117.00	937.9	294	110,000	228.60	481.7	151.0
120,000	227.00	526.4	165	115,000	317.90	360.5	113.0
125,000	365.00	370.0	116				

Mild steel forgings (wrought iron)				Cast iron			
B	H	u	u_r	B	H	u	u_r
10,000	3.76	2,567.0	833	10,000	20.00	497.6	156.0
20,000	4.70	4,252.0	1,333	20,000	32.90	609.3	191.0
30,000	5.64	5,091.0	1,596	30,000	51.40	583.4	183.0
40,000	7.20	5,547.0	1,739	40,000	82.10	488.1	153.0
50,000	9.40	5,318.0	1,667	50,000	134.00	370.0	116.0
60,000	13.90	4,351.0	1,364	60,000	224.00	266.7	83.6
65,000	16.00	4,070.0	1,275	65,000	322.00	201.3	63.1
70,000	20.40	3,436.0	1,077				
80,000	32.60	2,453.0	769				
90,000	62.60	1,436.0	450				
100,000	134.70	743.2	233				
105,000	197.20	532.7	167				
110,000	324.20	338.1	106				

B Flux density in lines per square inch.
H Ampere-turns per inch length.
u Absolute permeability, perms per inch cube.
u_r Relative permeability as compared with that of air.

FIG. 12. MAGNETIC PROPERTIES OF IRON AND STEEL

Assuming the magnetic circuit under consideration to be made of cast steel and to have a required flux density of 40,000 lines per square inch of section, we

find the corresponding number of ampere-turns required to be 13.40. In a like manner the value of H or ampere-turns per inch length of circuit for cast iron with a flux density of 60,000 lines per square inch is 224.

Permeability represened by u is, as learned in Chapter II, equal to B divided by H or the flux density in lines per square inch divided by the number of ampere-turns per inch length, so that H is equal to B divided by u. Referring to the table of the magnetic properties of iron and steel, Fig. 12, we find that for carbon sheet steel the value of H corresponding to 50,000 is 13.20, while that of u is 3796.0, the quotient obtained by dividing 50,000 by 13.20.

In calculating the number of ampere-turns required for a given generator or motor field winding, account must be taken not only of the metallic section of the magnetic circuit, but also for the air gaps existing between the faces of the pole pieces and that of the armature. This may be determined in the same manner as that employed for the other portion of the magnetic circuit except that for u a value of 3.19 must be employed, 3.19 being the number of perms permeability per inch cube of air.

Where the value of B is equal to 30,000, the required number of ampere-turns per inch length is equal to 30,000 divided by 3.19, or 9404. Similarly with a flux density of 90,000 lines per square inch H has a value of 28,213.

The values of relative permeability as given in the table, Fig. 12, are, it will be seen, equal in each case to the value of u or absolute permeability divided by 3.19.

Calculation of the Magnetic Circuit

THE ELECTROMOTIVE FORCE induced within the armature windings of a generator is, as explained in the first chapter of this book, directly proportional to the total flux, the value of which is in turn dependent upon the magnetic intensity or number of ampere-turns. Knowing the flux required, the total number of ampere-turns may be determined by calculating the number of ampere-turns necessary to produce this flux in each com-

ponent part of the magnetic circuit and taking the sum of such numbers of ampere-turns.

In a simple bi-polar machine, the magnetic circuit may, as indicated in Fig. 13, be made up of an armature of carbon steel laminations, two air gaps, two cast-iron pole pieces, two cast-iron cores and a yoke of wrought-iron here employed as a base for the machine.

Let us assume a maximum flux of 1,000,000 lines required, and that the base piece has a sectional area

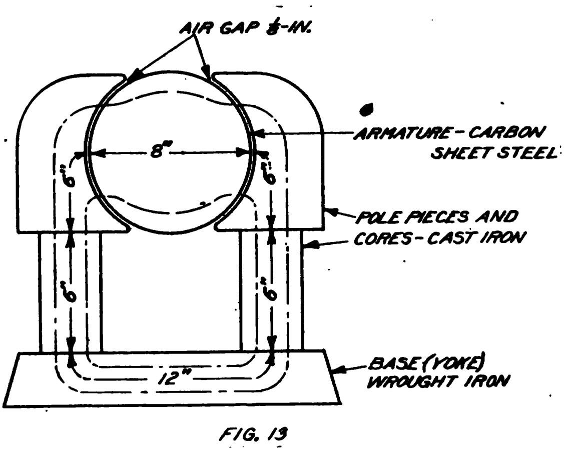


FIG. 13. ILLUSTRATING THE MAGNETIC CIRCUIT OF A TYPICAL BIPOLAR DYNAMO

of 15 sq. in., each of the cores 20 sq. in., each of the pole pieces a minimum section of 25 sq. in. and the armature 48 sq. in. The armature has a diameter of 8 in. or a circumference of 25.12 in., so that with each pole piece width of 6 in., each air gap (neglecting leakage) has a sectional area of ⅓ (under the assumption that each pole piece face covers ⅓ of the armature surface) times 25.12 times 6, or 50.24 sq. in.

The armature, which is made up of carbon sheet steel, has a maximum sectional area of 48 sq. in. and a length of, let us say, of 8 in. The flux density through this member of the machine is then 1,000,000, divided by 48, or 20,835 lines per square inch. Accepting 20,000

lines, we find the corresponding value of H for carbon sheet steel to be 7.20, which times 8 is equal to 57.60 ampere-turns.

Due to the reluctance of the path of air between the face of the pole pieces and the surface of the armature, a correction or leakage factor must be employed; that is, the total number of lines of flux required in the armature, or 1,000,000, in this particular case must be multiplied by a factor which in practice varies from 1.1 to 2.0, to determine the actual number of lines of force to be developed. Let us assume this factor, known as the leakage factor, to have a value of 1.3. Multiplying 1,000,000 by this, we obtain 1,300,000, the number of lines of force upon which the required number of ampere-turns must be based.

The armature has a circumference of 25.12 in., one-third of which, the portion covered by the face of each pole piece, is 8.37 in. This times $6 = 50.22$ sq. in., is the area of the section of the air path. Dividing 1,300,000 by 50.24, we obtain 25,875 lines as the flux density of each air gap.

The permeability of air is 3.19 perms for a 1-in. cube, so that the required number of ampere-turns per inch path is equal to 25,875, divided by 3.19, or 8111. The length of the two air gaps is, however, but 0.25 in., and as a consequence the actual number of ampere-teurns required is 8111 times 0.25, or 2027.7.

For the pole pieces, the area for passage of magnetic flux is 25 sq. in. and as they must carry the flux that enters the gap, the density will be $1,300,000 \div 25 = 52,000$ lines per sq. in. The value of H for $B = 52,000$ in cast iron is about 140. This times 12 gives 1680 ampere-turns for the pole pieces.

For the cores, $1,300,000 \div 20 = 65,000$ for B. The value of H for cast iron is 322, and this times 12, the total length of two cores, gives 3864 ampere-turns.

For the base, the value of B is $1,300,000 \div 15 = 86,667$, which is more than half way between the 80,000 and 90,000 values in the table for wrought iron. The value of H will be, say 52; and this times 12 gives 624 ampere-turns for the base.

We have then for the total magnetomotive force required:

Armature	57.6 a.t.
Gap	2027.7 a.t.
Poles	1680.0 a.t.
Cores	3864.0 a.t.
Base	624.0 a.t.
Total	8253.3 a.t.

Calculating Resistance of Conductors

The resistance of any electrical conductor varies according to the material of which it is composed, its length and its cross-sectional area. As the resistivity of the conductor (that is, its specific resistance or the resistance of a wire of unit length and of unit sectional area) decreases, as its length decreases and as its cross-sectional area increases, so will its resistance decrease. On the other hand, with an increase of resistivity, an increase of length and a decrease of cross-sectional area, the resistance will increase. This may be expressed numerically by the following formula:

$$R = p\,l \div a$$

where R is the resistance in ohms, p the specific resistance (which for commercial copper wire may be taken at 10.8, the resistance of a wire 1 mil in diameter and 1 ft. long), a the cross-sectional area of the wire in circular mils and l the length in feet.

Let us assume that the field coil of an electric generator is wound with 1000 ft. of No. 14 gage, B. & S. copper wire (the sectional area of which is 4110 cir. mils), and that it is desired to determine the resistance of this winding at ordinary room temperature.

Applying the above formula we have,

$$R = p\,l \div a = 10.8 \times 1000 \div 4110 = 2.63 \text{ ohms.}$$

Another factor, however, requiring consideration in calculating the resistance of any conductor is its temperature, for as the temperature increases the resistance increases, the rate of such increase depending upon the temperature coefficient of resistance of the given material. This coefficient, which in reality is the number

of ohms increase in resistance per degree rise in temperature, is, when based upon the Fahrenheit scale, equal to 0.0023 for high-grade commercial copper.

The total resistance R_t of any conductor at a temperature t deg. F. above initial temperature may then be determined by adding to the resistance in ohms at initial temperature, the product of the resistance in ohms at initial temperature, the temperature coefficient of resistance and the number of degrees rise in temperature, or

$$R_t = Ro + RoKt$$
$$= Ro\ (1 + Kt)$$

where Ro is the resistance of the conductor at initial temperature, K, the temperature coefficient of resistance and t the degrees Fahrenheit rise in temperature.

Where calculations are based on degrees Centigrade, the temperature coefficient of resistance is 0.00402.

If the winding of the coil referred to above has a resistance of 2.63 ohms at a temperature of 50 deg. F., its resistance at 120 deg. F. is equal to 2.63 $(1 + 0.0023 \times 70)$, or 3.05 ohms.

Coil Windings

Knowing the number of ampere-turns necessary to establish and maintain the required magnetic flux, the problem to be solved is the determination of the size of wire to use which, under the working voltage, will, with the proper number of turns, produce this number of ampere-turns.

The resistance of a conductor is equal to the product of 10.8 and the length in feet, divided by the sectional area in circular mils, so that when considering the resistance of the winding of a field coil, the following formula will apply:

$$R = (10.8 \times L' \times N) \div a$$

Where R is the resistance in ohms, L′ the length of the mean turn, as explained in Fig. 14, but expressed in feet, N the number of turns employed and a the sectional area of the conductor in circular mils.

For any particular machine the coil will receive current under some given voltage E, from the value of

which, together with that of R, we are, by the application of Ohm's law, readily enabled to calculate the value of the current flow. Current or I is equal to the quotient obtained by dividing the voltage E by the resistance R, and as we have just seen, R is equal to $(10.8 \times L' \times N) \div a$.

$$I = \frac{E}{(10.8 \times L' \times N) \div a}$$

or

$$I = \frac{E\,a}{10.8 \times L' \times N}$$

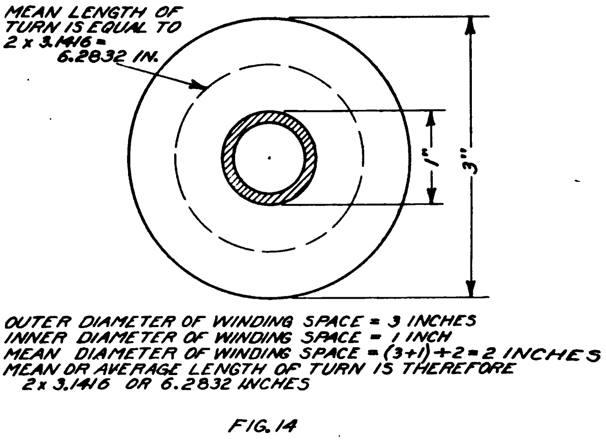


FIG. 14. EXEMPLIFYING MEAN LENGTH OF TURN

Multiplying each side of this equation by N, the value of the number of turns, we have

$$I\,N \text{ (ampere-turns)} = \frac{N\,E\,a}{10.8 \times L' \times N}$$

But, as N appears in both the numerator and the denominator of the right-hand side member of the equation, these cancel as follows:

$$I\,N \text{ (ampere-turns)} = \frac{E\,a}{10.8 \times L'}$$

Transposing, we have for the sectional area of the conductor,

$$a = \frac{10.8 \times L' \times I \times N}{E}$$

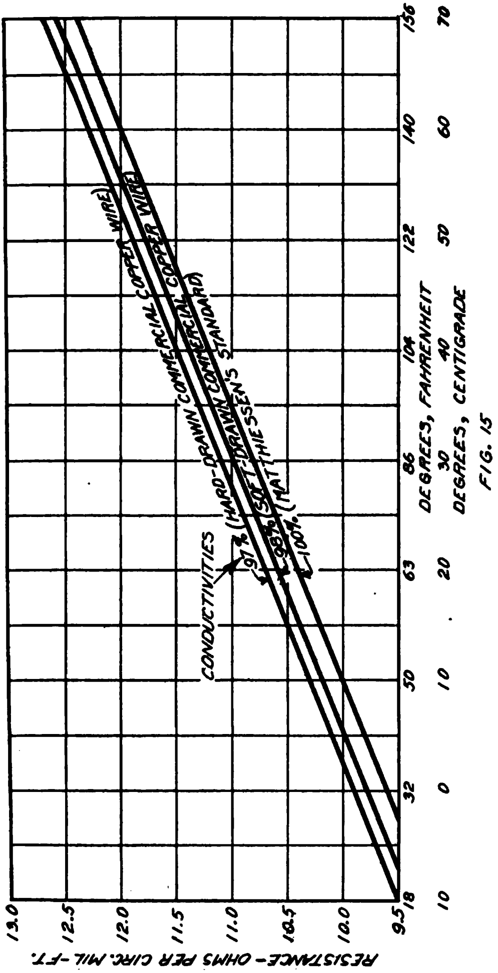


FIG. 15. CURVES SHOWING CHANGE IN SPECIFIC RESISTANCE WITH CHANGE IN TEMPERATURE FOR VARIOUS GRADES OF COPPER WIRE

Provision for Heating

In presenting the formula for calculating the resistance of a conductor, p or specific resistance was

accepted to have a value of 10.8 ohms. This, however, as may be seen by reference to the curves in Fig. 15, showing the resistance per circular mil foot of copper of different conductivities at various temperatures, is the resistance of a 1-ft. length of soft drawn commercial copper having a diameter of 1 mil, when at a temperature of about 75 deg. F. Obviously then, the above formula for the size of wire required for any particular coil is based upon a working temperature of 75 deg. F.

Should it be desired, therefore, to work the coil at any other temperature, the value of the specific resistance of the grade of copper employed at that other temperature will have to be used instead of 10.8. Assume that we desire to use a working temperature of 131 deg. F., and that the wire is of the soft commercial grade. The specific resistance to be used in our calculations will then, according to the curve, be 12.

Rate at which heat is generated per second in any wire is proportional to the square of the current and to the resistance; that is $W = R I^2$; where W is the amount of heat generated in watts by current I, and R the resistance of the wire.

And, as the temperature rise within a coil is dependent not only upon the value of W, but also upon the amount of external surface exposed to the air, at least 1 sq. in. of radiating surface should be provided for each ½ watt of $R I^2$ loss.

Questions on Chapter III

1. How do values of H compare for sheet steel, cast steel, wrought iron, cast iron and air, for a value of $B = 40{,}000$? Which metal is most effective for magnetic circuits?
2. Why are different metals used for various parts of the magnetic circuit in a dynamo?
3. What part of the magnetic circuit offers the greatest magnetic reluctance?
4. Make a sketch similar to Fig. 13 for the following dimensions:
   Armature—10 in. diam.; 12 in. long; hole in center, 5 in. diam.

Pole pieces—10 in. high; bored $10\frac{3}{8}$ in.; width from bore to back 4 in.; length along axis of armature 10 in.; cover $\frac{2}{3}$ of armature circumference.

Cores rectangular—$3\frac{1}{2}$ in. wide; 8 in. deep along axis of armature; 6 in. high, set central on bottoms of poles.

Base, rectangular—19 in. long; 6 in. high; 10 in. wide along axis of armature.

The armature is sheet steel, poles and cores cast steel, base cast iron. Total flux in armature, 1,800,000 lines; area of armature $= 5 \times 12 = 60$ sq. in.

Leakage factor $= 1.4$.

Compute the ampere-turns required for the magnetomotive force ($M = 5459.5$ a.t.).

$Aa = 5 \times 12 = 60$ sq. in.

$F = 1{,}800{,}000$ lines.

$la = 8.5$ in.

$$Ba = \frac{1{,}800{,}000}{60} = 30{,}000 \text{ lines.}$$

$Ha = 8.77$ a.t. $\quad Ma = 8.77 \times 8.5 = 74.5$ a.t.

F gap $= 1{,}800{,}000 \times 1.4 = 2{,}520{,}000$ lines.

Circum. a $= 31.42$ in.

$\frac{1}{3} = 10.45$ in.

Ag. $= 10.45 \times 10 = 104.5$ sq. in.

$$Bg = \frac{2{,}520{,}000}{104.5} = 24{,}100 \text{ lines}$$

$$Hg = \frac{24{,}100}{3.19} = 7550 \text{ a.t.}$$

$lg = \frac{3}{8} = 0.375$ in.

Mg. $= 7550 \times 0.375 = 2840$ a.t. for 2 gaps.

Fp. $= 2{,}520{,}000$ lines.

Ap. $= 4 \times 10 = 40$ sq. in.

$Bp = 63{,}000$ lines.

$Hp = 24.6$ a.t.

lp. $= 6$ in. $\quad Mp = 24.6 \times 12 = 295$ a.t. for 2 poles.

$Fc = 2{,}520{,}000$ lines

$Ac = 8 \times 3.5 = 28$ sq. in.

$lc = 12$ in.

$$Bc = \frac{2,520,000}{28} = 90,000 \text{ lines.}$$

Hc = 70 5 a.t.

Mc = 70.5 × 12 = 846.0 a.t. at 2 cores.

Fb = 2,520,000 lines.

Ab = 60 sq. in.

lb = 15 in.

$$Bb = \frac{2,520,000}{60} = 42,000 \text{ lines.}$$

Hb = 93.5 a.t.

Mb = 93.5 × 15 = 1404 a.t.

$$\begin{aligned} a &= 74.5 \\ g &= 2840.0 \\ p &= 295.0 \\ c &= 846.0 \\ b &= 1404.0 \\ \hline \text{M total} &= 5459.5 \text{ a.t.} \end{aligned}$$

5. On what does the resistance of a conductor depend? What is the temperature co-efficient?
6. What will be the value of p. for copper wire at 120 deg. if the value at 50 deg. is 10.8? (12.55 ohms.)
7. Allowing a thickness of field coil winding of 2 in. what will be the mean length of a turn in ft. for question 4, (2 7/12 ft.)
8. If No. 14 insulated wire will wind 13 turns per inch of length of coil, and 15.4 layers to the inch of depth, how many turns can be put into each coil, allowing ¼ in. for each coil head? (2130.)
9. What will be the feet of wire in the two coils? (11,005.)
10. What will be the resistance of the two coils in series? (28.93 ohms.)
11. What current will flow for an e.m.f. of 130 volts? (4.5 a.)
12. How many a.t. will this give? Will it be sufficient to give the required magnetomotive force? (19,170 a.t.)
13. What will be the R I^2 loss per coil? Will the radiating surface of the outside coil be sufficient? (Surf. = 214.5 sq. in.) (No.)

CHAPTER IV

THE SERIES GENERATOR

THEORY OF OPERATION, CHARACTERISTICS AND APPLICATION

WITH REFERENCE to the schemes of connections employed, there are practically but three types of direct-current dynamos, namely, the series wound, the shunt wound and the compound wound machine. The simplest of these is the series generator and while formerly employed quite extensively in connection with the early Brush and Thomson-Houston arc lighting systems, this machine is today practically out

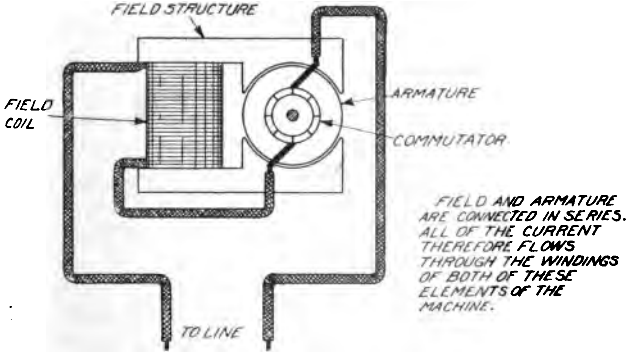


FIG. 16. DIAGRAM OF CONNECTIONS OF THE SERIES GENERATOR

of use except, perhaps, for special classes of service, as in the Thury system of high-voltage transmission employed to some extent upon the European continent. Figure 16 is an elementary diagram of connection of this type of generator.

Ordinarily, the field coil winding consists of a comparatively few turns of heavy wire connected as shown, and as the name of the machine implies, in series with

the armature. Due to the ability of the field structure to retain a slight degree of magnetism—termed residual magnetism—an electromotive force will be induced within the windings of the armature immediately upon this member being set in rotation, and the higher the speed attained, the greater will be the electromotive force developed. With the external circuit open, however, no current will flow, and as a consequence that electromotive force which is induced in the windings of the armature is limited by the speed of rotation.

Upon connecting a load across the terminals of the machine, the circuit is closed, and as a result a flow of current occurs, which in passing through the field

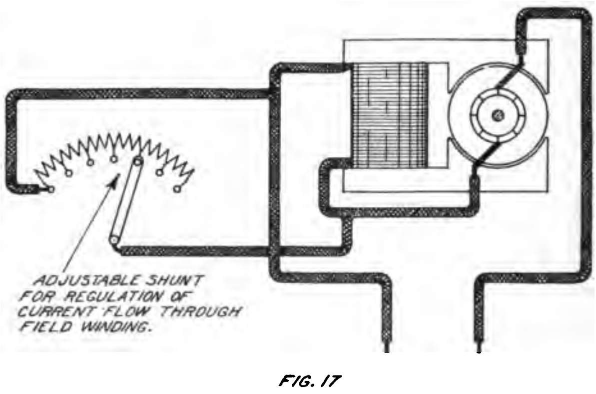


FIG. 17. DIAGRAM OF CONNECTIONS SHOWING METHOD OF ADJUSTING FIELD STRENGTH BY USE OF SHUNT

coil provides the necessary magneto-motive force by means of which an increase of magnetic flux is established. The armature conductors will therefore (assuming the speed to remain unchanged) be cutting a greater number of lines of force, thus producing a corresponding rise in voltage. It is obvious, then, that if more load be added to the terminals of the machine in such a manner as to reduce the value of the external resistance, increased field magnetism accompanied by increased voltage will result.

Where series machines have been employed, this scheme of load connection has generally not been used.

Instead of connecting the load in such a manner as to cause a decrease of external resistance, the various elements comprising the load were, as exemplified in the series arc lighting system, connected in series not only with the machine, but also with one another. With this scheme, an increase of load is followed by an increase of external resistance and a tendency on the part of the voltage to drop. This action may, however, be counteracted by the use of proper regulating devices, which cause a building up of the line voltage with an increase of load, the increase in voltage being dependent upon the resistance added to the circuit.

A simple means of regulating the voltage of a series generator is that shown in Fig. 17. By the employment of an adjustable shunt connected across the field winding, any desired portion of the total current flow may be caused to pass through the shunt, thereby limiting the amount of current passing through the field winding to that required for the excitation necessary to provide the required terminal voltage.

Series-wound generators are frequently called "constant-current" machines, not because they are inherently such, but because of the readiness with which they may be made to deliver constant current by the application of the proper regulating devices.

Rectification of Current

The electromotive force induced in a coil or set of coils revolving between the poles of a magnet is, as was explained in Chapter I, alternating in nature; that is, it alternates through positive and negative values; in other words, it is an alternating electromotive force and the current which is sent through a circuit by such an electromotive force is obviously an alternating current. Where, however, the machine is to deliver so-called direct or unidirectional current, means must be provided for its rectification. This is accomplished by means of a commutator consisting essentially of two or more copper bars connected to the windings in a manner to be explained later and supported parallel to the shaft by some form of framework, which not only insulates the

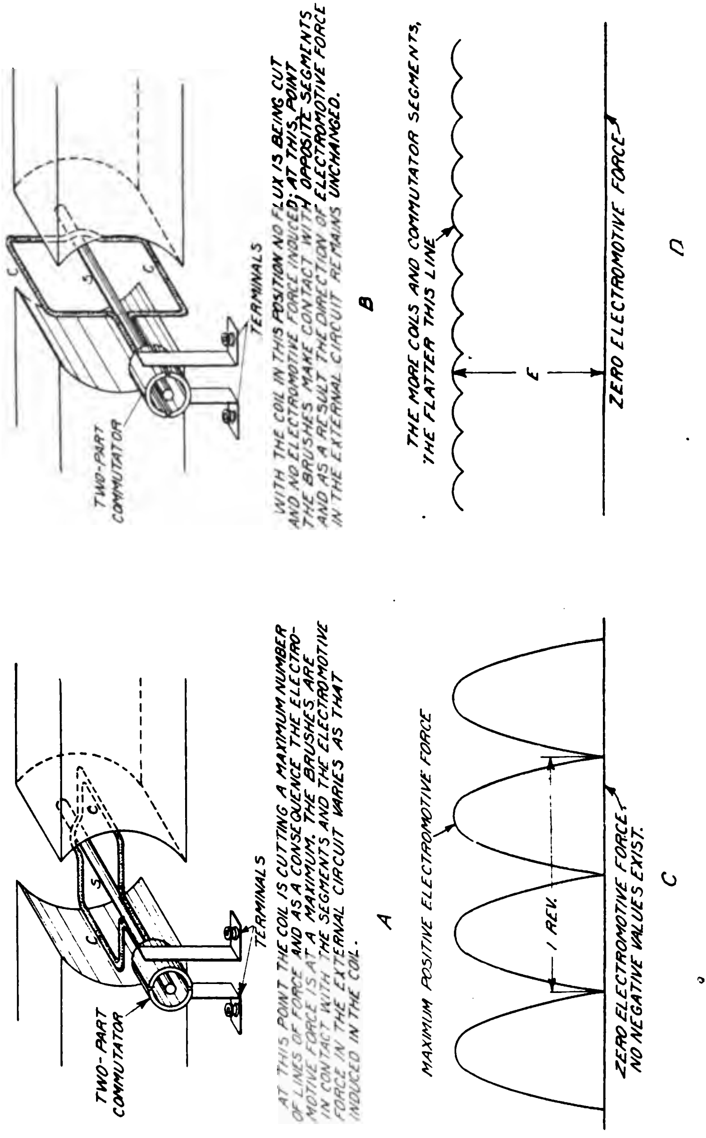


FIG. 18. RECTIFICATION OF CURRENT BY MEANS OF COMMUTATOR AND RESULTS PRODUCED

bars, one from another, but also from the shaft upon which the whole is mounted.

Where but a single coil revolving between the pole faces of a bi-polar machine is employed, the arrangement would be as indicated in Fig. 18. Coil C, mounted on Shaft S, has its terminals connected to metallic segments of the commutator (also carried by the shaft), with the center lines of the slots between the two segments perpendicular to the plane of the coil. Bearing against these segments are the brushes, to which in turn are connected the leads joining with the external circuit.

As the coil is made to revolve, an electromotive force is induced therein, this electromotive force reaching a

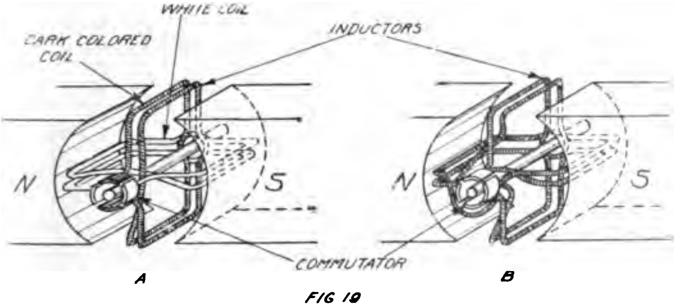


FIG. 19. OPEN AND CLOSED COIL ARMATURE WINDINGS

maximum value when the plane of the coil is parallel to the lines of force and a minimum value when the plane of the coil is perpendicular to the lines of force. As the coil moves to cut the maximum number of lines of force the brushes are as at A, in contact with the segments, and as a consequence the electromotive force (and current) will vary in the external circuit just as it varies within the coil. With continued rotation, the coil will reach such a position as will bring its plane perpendicular to the lines of force, as at B, at which point the direction of electromotive force induced within the coil is changed, while, due to the fact that at this point of the cycle each of the segments is brought into contact with the other brush, the direction of electromotive force (and current) in the external circuit re-

mains unchanged. As a consequence the electromotive force curve will be as shown at C, and as the number of coils (and commutator bars) increases the electromotive force curve will tend to assume the form of a wavy line, such as at D.

By the employment of two coils placed at right angles with one another, and each provided with its own set of segments, the electromotive force curves are as shown at C, Fig. 18, but with the two curves displaced by 90 deg. If, however, these coils instead of being connected "open" as the form of connection in Figs. 18 and 19-A is termed, be connected as at B, Fig. 19, the resultant electromotive will be equal to the sum of that induced in each of the coils.

ARMATURE REACTION AND FIELD DISTORTION

TWO DISTINCT ACTIONS, the combined effect of which is termed armature reaction, occur in every dynamo electric machine; one of these is termed the demagnetizing action, while the other is referred to as the cross magnetizing action, or, in other words, demagnetization and cross magnetization, respectively.

In Fig. 20 is shown, placed between the two poles N and S, a so-called ring armature consisting of an iron ring upon which are wound eight coils, A, B, C, etc., and connected to eight commutator bars in the manner indicated. Due to their position in relation to the poles of the magnet, coils C and G are cutting a maximum number of lines of force, and as a consequence have induced in them maximum electromotive force. In the case of coils B, D, F and H the electromotive force induced is considerably less than that induced in coils C and G, while in coils A and E practically no electromotive exists.

As may be observed by the arrows, the direction of the electromotive force induced in each of the coils on each side of the armature is the same, while that induced in the coils on one side of the armature is opposite to that induced in those on the opposite side. With the brushes, therefore, placed as shown, the current leaves the armature at the upper brush and after

traversing the field coil and the external circuit returns by way of the lower brush, half passing through the right-hand side of the winding and the other half through the left-hand side.

It will be observed that each brush for the position shown bears upon two commutator bars, so that the upper brush takes current directly from coils B and H,

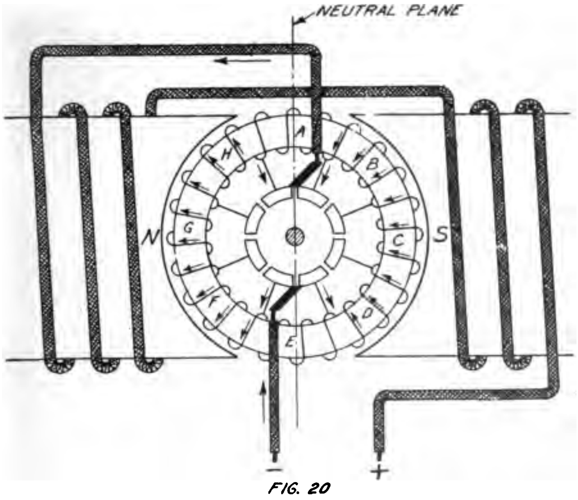


FIG. 20. TYPICAL SERIES GENERATOR WITH RING-WOUND ARMATURE

while the lower brush conducts it to coils D and F. Each brush is of sufficient width to bridge the insulation between any two commutator bars, and by locating the brushes in the plane (termed the neutral plane) indicated in Fig. 20, the coil in which a minimum electromotive force is being induced is momentarily short-circuited, after which, due to the change in direction of motion of the coil, relative to the direction of the magnetic flux, the direction of the induced electromotive force also is changed. This may be readily understood by noting the direction of rotation of the armature (clockwise) and the direction of the induced electromotive force in coil B and the direction of that in coil H.

Although the electromotive forces in coils A and E are comparatively low in value, the current flow, due to the short-circuiting of the coils, may become excessive, resulting in destructive sparking. To avoid this it is customary to employ high-resistance brushes; the short-circuit current and consequently the resulting sparking are thereby reduced to a minimum.

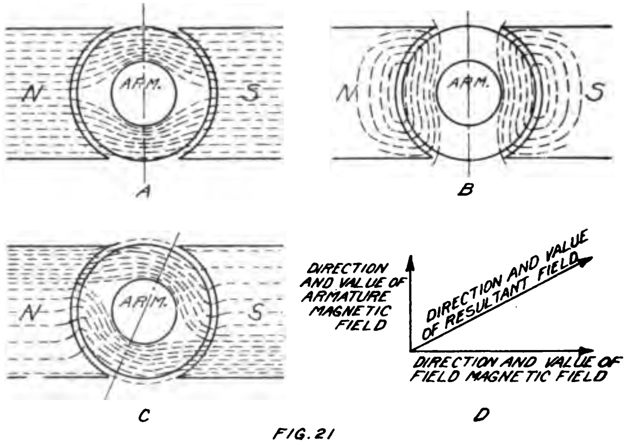


FIG. 21. ILLUSTRATING FIELD DISTORTION CAUSED BY COMBINED FIELD AND ARMATURE MAGNETIZATION

Assume sketch (A) Fig. 21 to represent an armature (Arm) between poles N and S of a bipolar dynamo, and that no current is flowing through the windings of the armature while the fields are fully excited. As a result, the established magnetic flux will pass from pole N through the structure of the armature in the manner indicated, and thence on to pole S. If, however, the field poles remain unmagnetized, while a current of electricity from some external source is caused to pass through the windings of the armature, a magnetic field of the character shown at B will be set up.

When a generator, the field of which is properly (and externally) excited is brought up to speed, but remains unloaded, no current passes through the armature and the form of the magnetic field will be as illus-

trated at A. The armature coils in which minimum electromotive force is then induced are as shown in Fig. 20, those lying in a vertical plane midway between the two pole pieces, and as a consequence, in order to realize sparkless commutation, the brushes will be placed as indicated. If, however, the external circuit is closed (that is, the machine loaded) a current will pass through the armature windings, which will tend to create a magnetic field as at B, Fig. 21, but on account of the existing magnetic field, due to the field excitation, a resultant field of a character shown at C will be created, thus causing a crowding of the magnetic

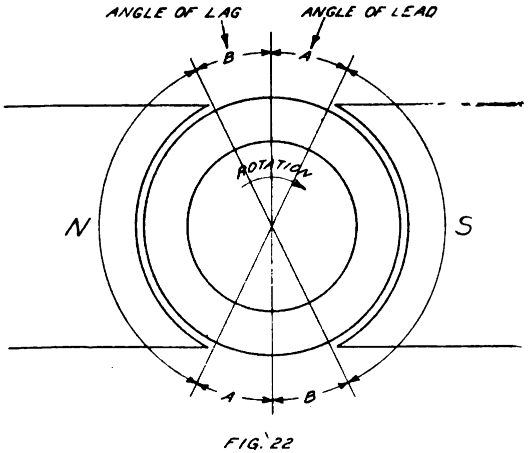


FIG. 22 IN THE GENERATOR WE HAVE THE ANGLE OF LEAD; IN THE MOTOR THE ANGLE OF LAG

lines of force at the tips of the poles under which the conductors leave and a weakening of the field at the tips which the conductors approach. It is, therefore, apparent that the minimum number of lines of force cut will be not, as in Fig. 20, along an axis perpendicular to the center line of the pole pieces, but slightly advanced in the direction of rotation. This necessitates a shifting of the brushes, the degree of advance from their mid position being called the angle of lead.

In the case of a motor, however, the distortion of the magnetic field is such as to require a backward

shifting of the brushes; that is, instead of shifting the brushes forward through an angle A, as in Figs. 21C and 22, they must be shifted backward through angle B, ordinarily called the angle of lag.

The conductors included within angles A and B are referred to as the back ampere turns and their magnetizing effect, which is opposed to and tends to weaken that created by the fields, is termed the demagnetizing action of the armature. The remaining turns of armature winding—that is, those not included within angles

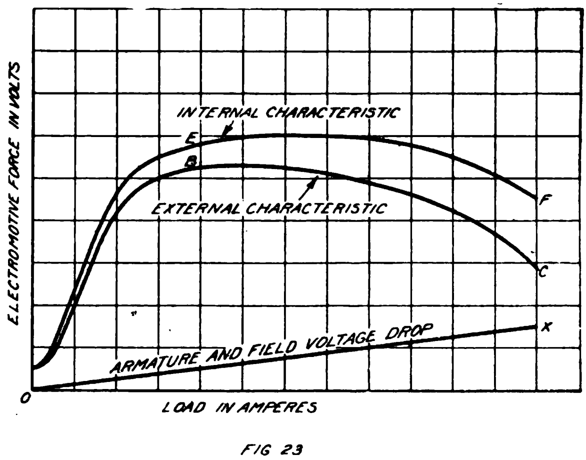


FIG. 23. CHARACTERISTICS OF THE SERIES GENERATOR

A and B—tend to create a field at right angles to the main field, and their effect is termed the cross magnetizing action of the armature.

CHARACTERISTICS

DUE to the presence of residual magnetism, a slight electromotive force is induced within the armature windings of a series generator as shown in Fig. 23. By adding load, however—that is, by reducing the resistance of the external circuit—a flow of current is established which in passing through the field windings produces increased flux, and that in turn (assuming constant armature speed of rotation) increases electro-

motive force. This building up of the voltage continues until the internal voltage drop in the armature becomes excessive, when added current flow results in a dropping off of the voltage in the manner indicated by B C.

The curve representing the armature and field voltage, or R I drop, is , as shown, a straight line, and if the various values of O X be added to the corresponding values of A, B, C, curve A, E, F is obtained. This is known as the internal characteristic of the machine and indicates the manner in which the electromotive force induced within the armature windings varies with the increase of load.

Questions on Chapter IV

1. How are field and armature windings connected in a series generator?
2. What is residual magnetism? Of what use is it?
3. What effect does adding load have on a series generator?
4. Why is a field shunt used?
5. What is the purpose of the commutator? How many bars are used to a coil?
6. What should be the position of the coil when the brushes pass from its connected commutator bars?
7. How is a steady e.m.f. secured?
8. What is the effect of the armature winding on the magnetic field? How does this affect commutation?
9. What is brush lead? Lag?
10. What effect do field and armature resistance have on the voltage at the terminals of the series generator?

CHAPTER V

SHUNT AND COMPOUND WOUND GENERATORS

Reasons for Windings, Characteristics, Uses for Which Fitted

IN the series-wound machine in which the field winding is connected in series with the armature, increase of current flow reacts upon the field, strengthening it and thereby providing increased electromotive force. In other words, with speed remaining fixed, the electromotive force induced within the armature winding varies as the flow of current through the field coils.

If the field is made up of a highly magnetized permanent magnet (such as used in magnetos), the electromotive force produced is dependent upon the speed of the armature and if that remains unchanged, the electromotive force remains unchanged. A constant electromotive force or voltage is produced and the machine is termed a constant voltage or constant potential generator. The use of permanent magnets is, however impracticable and in order to provide a so-called constant voltage or potential the shunt-wound machine as shown at (A) Fig 24, was devised. In this type of generator the line leads connect directly with the brushes and instead of all of the line current passing through the field winding, but a small part of that delivered by the armature is utilized for the purpose of excitation.

As the armature is set in rotation, due to the residual magnetism of the field a slight electromotive force is created which forces a small current through the field winding with the consequence that the magnetomotive force and the resulting magnetic flux are increased, thus aiding in the building up of the voltage. With increased speed a greater electromotive force is produced, more current is caused to flow through the field winding and the voltage continues to rise in value. With the armature rotating at its rated speed and other conditions re-

maining unchanged, the field strength remains fixed and as the resistance of the winding remains constant the field strength and consequently the voltage can only be altered by the use of a variable resistance or rheostat, connected as shown at (A) Fig. 24. If, therefore, the speed of a shunt-wound generator is constant, and its load remains fixed, the electromotive force of such a machine can be varied only by changing the resistance of the shunt field winding circuit, that is by altering

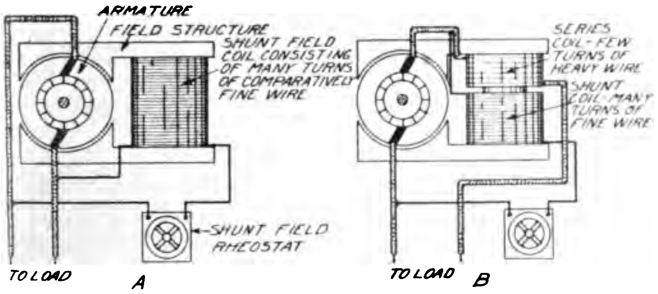


FIG. 24. GENERAL ARRANGEMENTS AND SCHEMES OF CONNECTIONS OF (A) SHUNT-WOUND AND (B) COMPOUND-WOUND MACHINES

the setting of the rheostat. Increasing the resistance will lower the electromotive force while decreasing the resistance causes a rise in voltage.

Effect of Armature Drop on Voltage

If, however, the load on the generator increases, more current will flow through the winding of the armature; and although (assuming the field strength to remain constant) the electromotive force induced in the conductors of the armature is of fixed value, the terminal voltage due to the R I drop will decrease. This in turn will decrease the flow of current through the field winding, the field will weaken, and a further drop of voltage will result. With added load, this action will cause a continued drop in terminal electromotive force and if the

load (current flow through armature) is excessive, the machine will "unbuild" or demagnetize and the voltage as indicated in Fig. 25 will tend to drop to zero; practically, it does not do so, however, owing to residual magnetism.

That external circuit resistance which is low enough to cause a shunt generator to demagnetize thus rapidly is termed the critical resistance for that particular machine.

Characteristic Curves and Determination of External Circuit Resistance

Three characteristic curves are to be considered, the external, the internal and the total. The first of

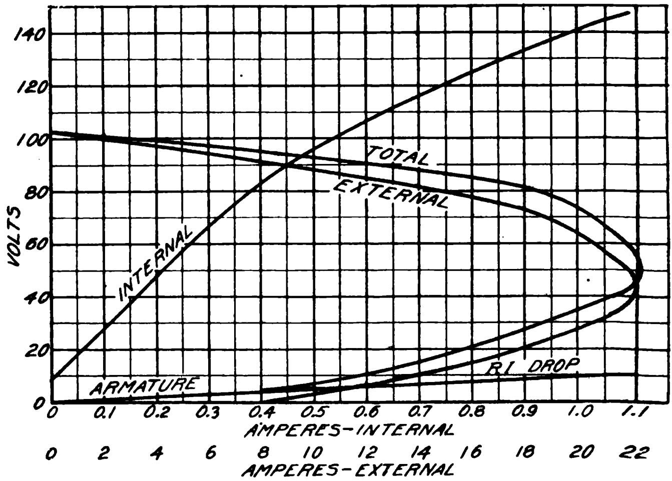


FIG. 25. CHARACTERISTIC CURVES OF A SHUNT-WOUND GENERATOR

these is that in which the terminal volts are plotted against the amperes flow through the external circuit and as shown in Fig. 25, consists of a loop. Starting at maximum voltage and zero current it follows a gradually

sloping path, when suddenly it turns, doubles back and tends to approach zero-zero.

The internal characteristic taken by plotting terminal volts against the amperes in the shunt circuit (with outside circuit open) is like the curve for a series machine. It rises steeply at first and then bends over as the saturation of the field cores becomes noticeable.

To obtain the total characteristic curve the total volts generated by the machine are plotted against the total current. This curve may, however, be obtained in an-

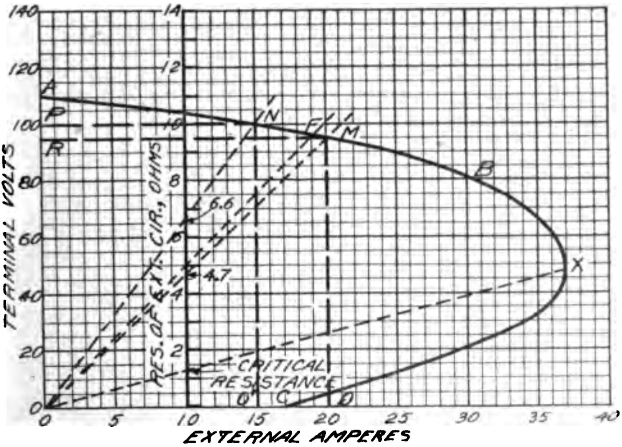


FIG. 26. CHARACTERISTIC CURVE OF A SMALL SHUNT-WOUND GENERATOR AND METHOD OF OBTAINING RESISTANCE OF EXTERNAL CIRCUIT

other way, knowing the resistance of the armature winding plot an armature R I drop curve, such as shown in Fig. 25, the various points for such a curve being obtained by multiplying the resistance of the armature winding in ohms by the flow of current in the armature in amperes. Adding to the external characteristic curve, corresponding value of armature R I drop will produce the total characteristic curve.

Shown in Fig. 26 is the external characteristic curve of a typical small shunt-wound generator, obtained by plotting instantaneous readings of instruments connected

as indicated in Fig. 27, G is the generator, A an ammeter, V a voltmeter and L the load. As the load increases, that is as more resistance is connected in parallel across the main lines, the total resistance of the external circuit decreases and as a consequence an increased flow of current takes place. In other words, as the external resistance decreases, the current flow increases, and as the instantaneous ammeter and voltmeter readings are

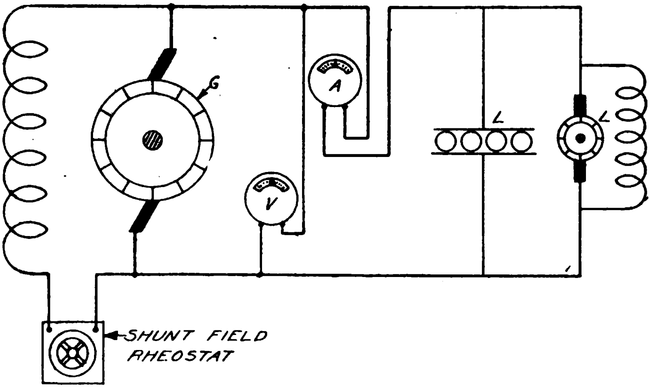


FIG. 27. SCHEME OF CONNECTION AND ARRANGEMENT OF INSTRUMENTS EMPLOYED TO OBTAIN EXTERNAL CHARACTERISTICS OF SHUNT-WOUND GENERATOR

obtainable throughout the range of rated capacity, the value of the external resistance at any point of the external characteristic may be readily determined by the application of Ohm's Law. The resistance of any circuit is equal to the applied electromotive force in volts divided by the current in amperes.

Referring to Fig. 26, we find that with a flow of 15 amp. through the external circuit the terminal voltage is 100 and that the value of the external resistance corresponding to point N (the intersection of O′ N and P N) is equal to 100 divided by 15, or 6.6 ohms. Similarly, the

voltage with a flow of 20 amp. is 95 and the resistance of the external circuit corresponding to point M (the intersection of Q M and R M) is equal to 95 divided by 20, or 4.7 ohms.

Having plotted the characteristic curve of any shunt-wound generator, a scale may be incorporated by means of which the value of the resistance of the external circuit (expressed in ohms) corresponding to any point on the characteristic curve is readily obtainable. This scale may be erected at any point although for convenience the 10-amp. ordinate has been selected, and it is obvious that by drawing O N the point of intersection of this with the vertical ordinate locates the point representing 6.6 ohms. In a like manner, the point representing 4.7 ohms is at the intersection of O M and the vertical ordinate.

Again referring to Ohm's Law, we find the value of electromotive force in volts equal to the product of the resistance in ohms and the current in amperes. With the particular location chosen, the 10-amp. ordinate, the current is 10 amp. and with a resistance of 2 ohms, we find the value of the electromotive force equal to 2 times 10 or 20 volts; hence 2 ohms will fall on the 20 volt horizontal. When the resistance is 4 ohms the corresponding electromotive force is 40 v. When 8 ohms the electromotive force is 80 v. and so on.

Having erected and completed the scale, the value of the resistance of the external circuit corresponding to any point on the characteristic curve such as let us say F, may be determined by running a straight line from the origin (or zero-zero) to point F. The reading of the resistance scale at the point of intersection of O F is the value of the resistance of the external circuit, in this particular instance 5.

X in Fig. 26 is the knee of the characteristic curve and indicates the maximum load the machine will carry before demagnetization. Joining this point with zero-zero, we have O X, the intersection of which with the resistance scale indicates the critical resistance of the particular generator to be approximately 1.25 ohms.

The critical resistance of any shunt-wound generator

is that resistance of the external circuit which will cause the generator to unbuild or demagnetize.

Application of Shunt Machines

Within a limited range of load the shunt-wound generator is essentially a constant voltage machine. It is used to but a limited extent at the present time because of the more satisfactory results obtainable by the employment of compound-wound generators.

Compound-Wound Machines

In the case of series-wound machines, increase of load results in increase of field magnetization and as a

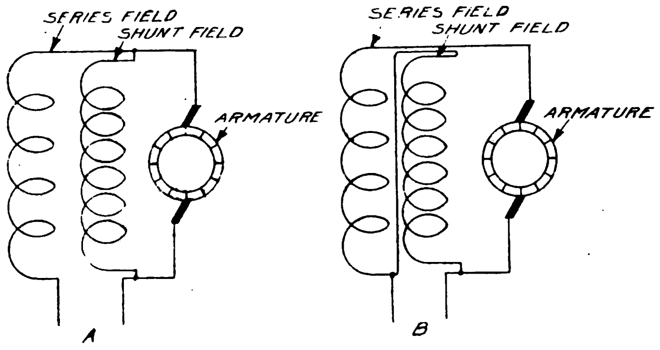


FIG. 28. DIAGRAMMATIC REPRESENTATION OF (A) SHORT AND (B) LONG SHUNT-COMPOUND-WOUND GENERATOR

result the voltage will tend to rise while with the shunt-wound generator as just explained, the voltage, due primarily to the armature R I drop, has a tendency to decrease in value. It is obvious, therefore, that due to these characteristics, series and shunt-wound machines are not, unless provided with more or less elaborate regulating devices, capable of maintaining constant voltage throughout the range of their rated capacities.

If, however, the pole pieces of a generator are provided with two sets of windings, one as in the case of the series machine, made up of a comparatively small

number of turns of heavy wire and connected in series with the armature, and the other made up of a large number of turns of fine wire connected as in the case of the shunt generator across the armature, the characteristics of the machine will naturally be a combination of those of a series and a shunt-wound generator. Machines so fitted with shunt and series windings are known as compound-wound generators, and by properly proportioning the number of series and the number of shunt winding turns, the terminal voltage made be made to remain practically constant throughout a wide range of

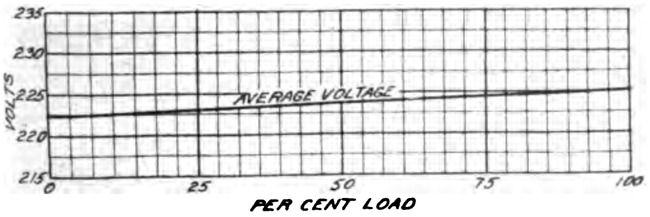


FIG. 29. CHARACTERISTIC OF A TYPICAL OVER-COMPOUND-WOUND GENERATOR

load, or if so desired the voltage may be made to increase slightly with increase of load. Machines in which the voltage is maintained practically constant are generally referred to as flat compound-wound generators, while those given a rising characteristic are termed over-compounded generators.

The degree of overcompounding ordinarily employed is such as to provide a full load terminal voltage of from 2 to 12 per cent in excess of the no-load terminal voltage.

Schemes of connections of compound-wound generators are shown in Fig. 28, that at A, where the shunt winding is connected directly across the armature, being known as the ordinary or short shunt connection, while that at B, where the shunt winding is in series with the series coil is the so-called long-shunt connection. Due to the comparatively low resistance of the series field winding, there is but little difference in the performance

of short and long-shunt-connected compound-wound generators.

Characteristics of over and flat compound-wound machines are illustrated in Figs. 29 and 30 respectively.

Application

Compound-wound generators are now used almost exclusively for direct current light and power service. Where such machines feed long lines along which the voltage drop is considerable, and it is desired to main-

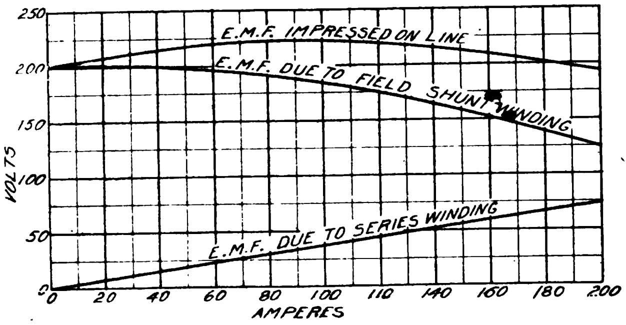


FIG. 30. CHARACTERISTICS OF A TYPICAL FLAT COMPOUND-WOUND GENERATOR

tain machine voltage at the point of utilization, over-compound generators are of considerable value.

Interpoles and Compensating Windings

In the ordinary direct-current generator carrying excessive loads, more or less difficulty is encountered with the sparking of the brushes where they make contact with the commutator. This is attributable to the fact that, as the flow of current through the armature winding exceeds a nominal value, excessive distortion of the field will result and as a consequence those armature coils in which reversal of direction of induced electromotive force is taking place are no longer the ones short-circuited by the brushes. Instead, the brushes are short circuiting coils in which a considerable electro-

motive force is being induced, thus causing sparking detrimental to both brush and commutator.

To prevent this action and to insure sparkless commutation under all conditions of operation, many generators are provided with auxiliary poles called inter-

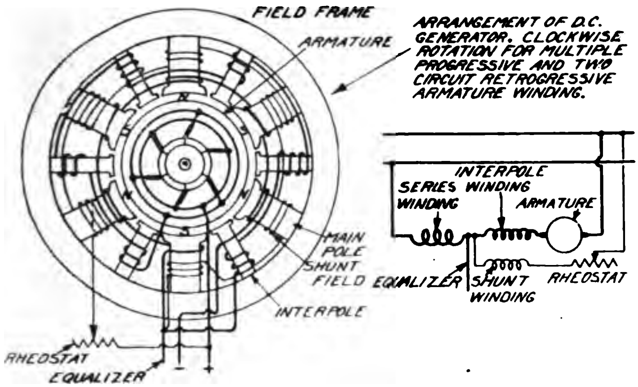


FIG. 31. INTERPOLE GENERATOR DIAGRAMS

poles and placed midway between the main pole pieces as indicated in Fig. 31. The windings on these poles, which are connected in series with the armature, establish within the cores a magnetic flux, which opposes the field set up by the armature-current, and of such value and direc-

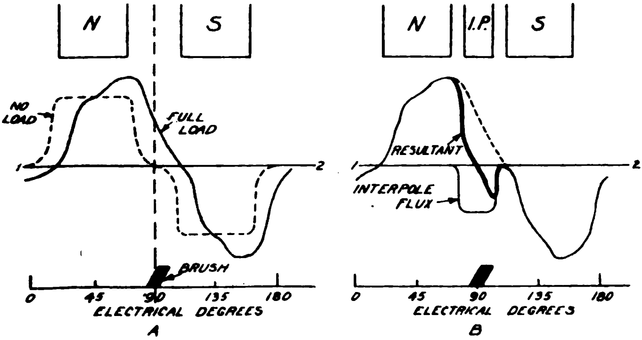


FIG. 32. EFFECT OF INTERPOLE UPON GENERATOR FIELD

tion as to produce within the coil or coils being short-circuited by the brushes, an electromotive force, which will insure reversal of the current in such coil or coils, while still under the brush.

In the case of generators, interpole connections are made such as to provide an interpole polarity the same as that of the following main pole. The interpole am-

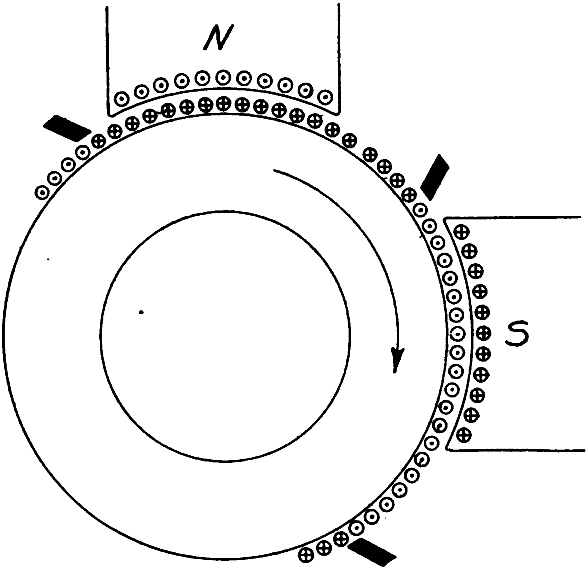


FIG. 33. ARRANGEMENT OF COMPENSATING WINDINGS

pere-turns per pole for a newly designed machine are usually made equal to 1.4 times the armature ampere-turns per pole. This is, however, as a rule too large, and adjustment must be made with a shunt after the machine is erected.

The effect of interpoles upon the magnetic field of a generator is shown in Fig. 32. With no current flow through the armature, a graphical representation of the magnetic flux of two adjacent pole pieces would be as indicated by the dotted line at A, while with the distortion due to armature reaction, the curve would assume

the form shown by the full line. As will be noted, unless the brush be shifted forward, this line crosses the neutral axis at some point beyond that at which the dotted line crosses, and as a consequence sparking will result as explained. If, however, an interpole is placed between the two main poles in the manner indicated at B, Fig. 32, the curve representing the resultant field will cross the horizontal axis 1—2, where this intersects the line midway between the two main pole pieces. In this way, the coils short-circuited by the brushes are retained within that part of the field in which the direction of electromotive force is reversed, and sparkless commutation thereby assured.

Another means by which armature reaction may be reduced is by the employment of so-called compensating windings, which consist of a layer of wires, parallel to the armature shaft, embedded in the pole faces as shown in Fig. 33. This winding is so connected that all or a part of the armature current flows through each wire as indicated by the dots and crosses.

Questions on Chapter V

1. What is the connection for a shunt-wound generator?
2. How does the voltage in a shunt-wound generator change as load increases?
3. What would be the effect on voltage of increasing the speed of a shunt-wound generator?
4. What is the object of the field rheostat ?
5. What is the external characteristic of a dynamo? The internal? The total characteristic?
6. What are the objections to an armature winding having high resistance?
7. Construct the external characteristic for a generator which showed the following readings on test.

Amperes (external) ...	0	10	20	30	40	50	60	70
Terminal Volts..	220	195	191	188	182	171	161	145
Amperes	80	85	80	70	60	50	40	35
Volts	120	80	50	36	25	15	5	0

8. Construct the external resistance scale on the 20-ampere vertical. What will be the resistance value on the 70-volt horizontal? What will be the current for an external resistance of 20 ohms? (35 ohms, 75 amp.)
9. What is "flat" compounding? Over-compounding? Which requires the greater number of ampere-turns in the series coil?
10. What is the difference between long shunt and short shunt connection?
11. What two methods of special winding are used to replace compounding?

CHAPTER VI

ARMATURE DETAILS

WINDINGS, COMMUTATORS AND BRUSHES

ONE OF the earliest types of armature windings was the Gramme ring which will be reviewed here only for the purpose of making more readily understood, the principle of operation and construction of the type now in general use, the drum wound armature. Essentially the Gramme ring armature as shown in Fig. 34 and as its name implies consists of an iron

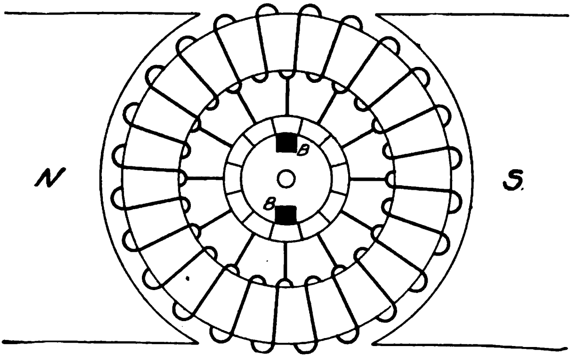


FIG. 34. A TYPICAL GRAMME RING ARMATURE WINDING

structure of ring shape and with a so-called ring (sometimes termed helical) winding in which all of the conductors are connected in series. As explained in a preceding chapter, all of the conductors on one side of the neutral axis have induced within them an electromotive force equal to, but opposite in direction to that induced in the conductors on the other side of the neutral axis; however, due to these equal and opposite electromotive forces, no current can flow until brushes B and B are brought into contact with the commutator.

Just what occurs within an armature winding of this type is shown in Fig. 35. Only those sections of the windings on the outside of the supporting ring are active in the cutting of the magnetic flux and have, therefore, an electromotive force induced within them; for this reason, they are termed inductors. The remaining sections act merely as connecting links between the various inductors and although they are conductors, no electromotive force is induced within them.

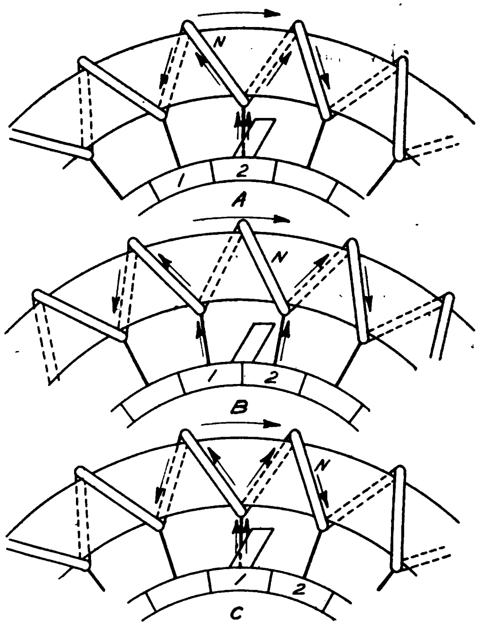


FIG. 35. SECTION OF GRAMME RING WINDING SHOWING PATH OF CURRENT IN COIL UNDER COMMUTATION

Let us, for example, consider coil N, Fig. 35, and assume that the armature is rotating as indicated by the arrow in a clock-wise direction. Current is seen flowing in through the upper brush, commutator segment 2 and the attached connecting lead after which it divides, half going through the right-hand section of the winding and the other half through the left-hand

section of which coil N is a part. However, as the armature moves forward, coil N enters the neutral plane (that is where the inductor of this coil cuts no magnetic flux) and as shown at B is at once short-circuited by the brush with the result that instead of the current passing through but one connecting lead, those attached to segments 1 and 2 are utilized.

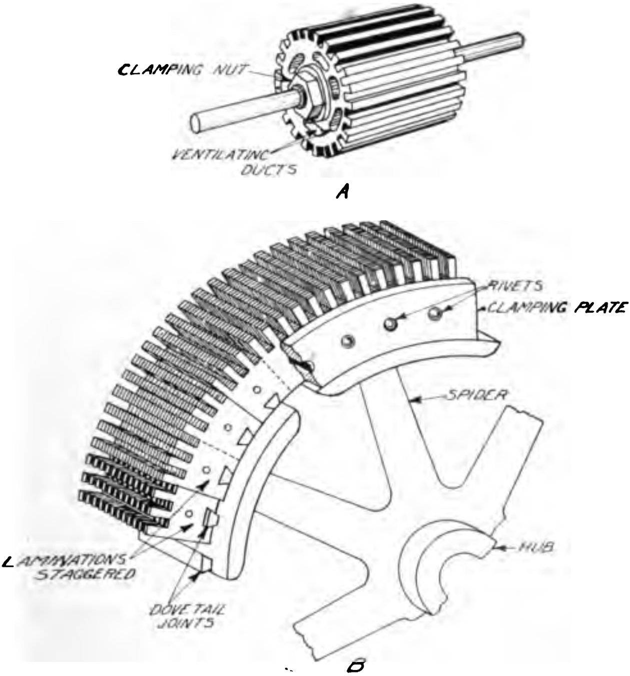


FIG. 36. TYPICAL DRUM ARMATURE CORES

With further advance of coil N, it again enters the magnetic field, but as the direction of its motion relative to the direction of the magnetic lines of force, has been reversed, the induced electromotive force and consequently also the direction of current flow is reversed as indicated at C.

THE DRUM ARMATURE

IN THE CASE of the so-called drum armature, cores of the forms shown in Fig. 36 and built up of iron lamina-

tions well annealed and insulated one from the other by means either of a thin coating of rust or some high-grade insulating varnish are employed. Those used in connection with the smaller machines are mounted directly on the armature shaft being held in place by means of iron end heads secured by some form of lock nut while on large machines, the laminations are mounted on cast spiders thus not only eliminating the employment of much otherwise useless material and thereby reducing the weight of the structure, but also assisting in providing more satisfactory ventilation. To facilitate manufacture, handling and assembly, sectional laminations are used on the large armatures, which also are provided with ducts allowing the passage of air from the interior to the exterior of the armature core.

Purpose of Laminations

Where a piece of iron such as the armature of a dynamo is rapidly alternately magnetized and demagnetized, an electromotive force is induced which sets up the flow of currents generally referred to as eddy currents. The flow of such currents in the case of an armature is in a direction parallel to the axis of the shaft. Naturally as may be expected, the existence of eddy currents is accompanied by considerable heating and in order to reduce the eddy currents, and the detrimental effects of their presence, the laminated form of structure is employed. Thickness of lamination used is dependent upon the number of magnetic reversals. In direct-current machines of moderate size, the armature core is subject to from 15 to 60 or more cycles per second, and the laminations are usually made from 0.020 to 0.035 in. in thickness.

Drum Windings

Although the armature core has for simplicity been omitted, Fig. 19, Chapter IV illustrates the elementary type of drum armature used in connection with a bipolar machine, the wire being wound lengthwise (parallel to the shaft) and diametrically across the ends. In a drum armature for a multipolar machine, the wire

is wound lengthwise on the outside surface of the core and across the ends, along chords of nearly 90 deg. for a 4-pole dynamo, along chords of nearly 60 deg. for a 6-pole field, and along chords of nearly 45 deg. for an 8-pole field. The approximate spacing between conduct-

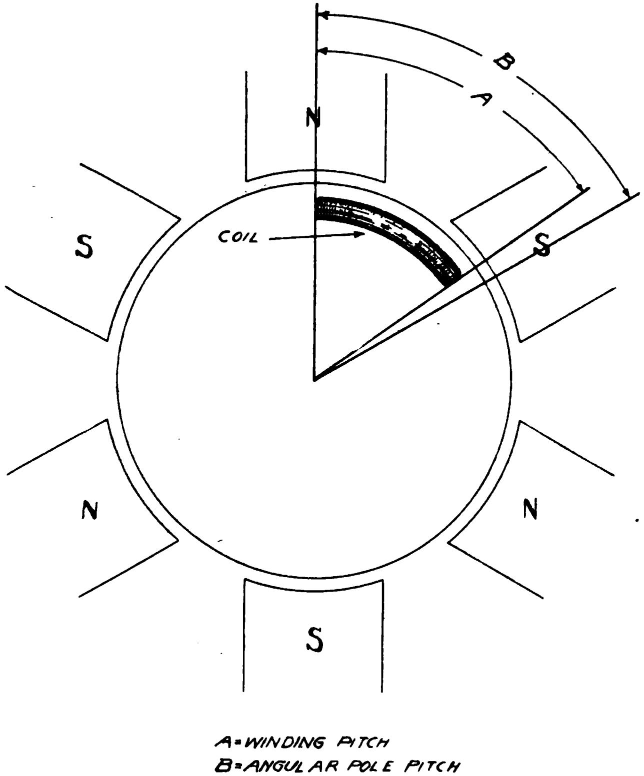


FIG. 37. ILLUSTRATING WINDING PITCH AND ANGULAR POLE PITCH

ors of a given coil is equal to 360 divided by the number of field poles.

Spacing of an armature coil in the case of a 6-pole machine is as shown in Fig. 37. Angle A is called the angular pitch or spread of the coil, or the winding pitch, while angle B is the angular pole pitch.

In Figs. 38 and 39 are shown two types of drum winding, the lap and the wave respectively. There is no essential difference between these two schemes in the case of a bipolar dynamo; but in the case of multipolar ma-

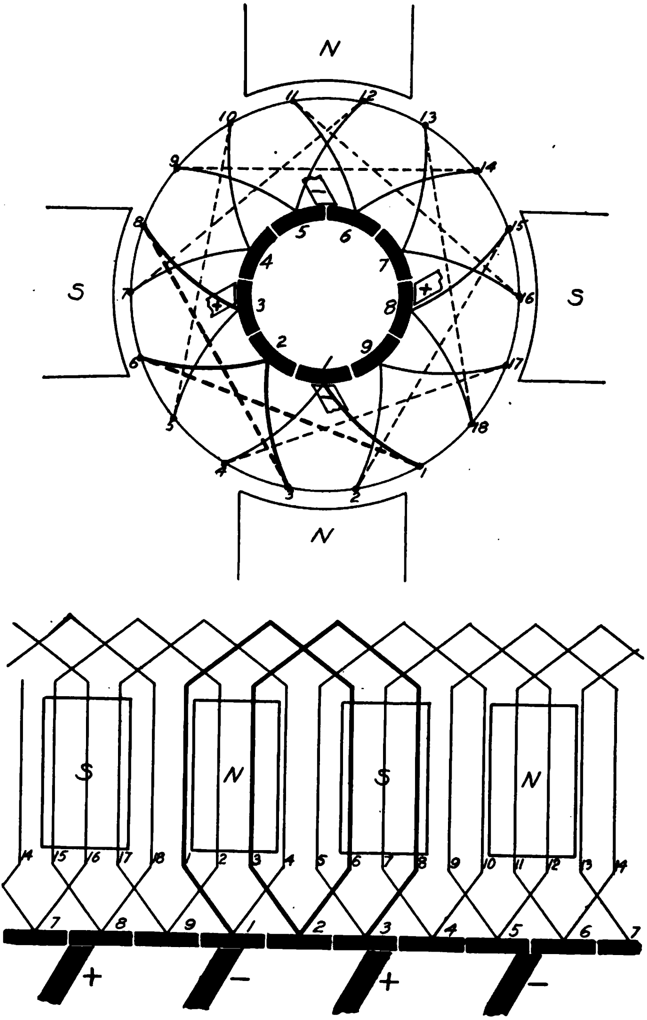


FIG. 38. SCHEME OF CONNECTIONS OF A LAP-WOUND ARMATURE

chines, the lap winding always provides as many paths between the brushes, as there are field poles, while with the simple wave winding, there are always two paths between the brushes regardless of the number of field poles.

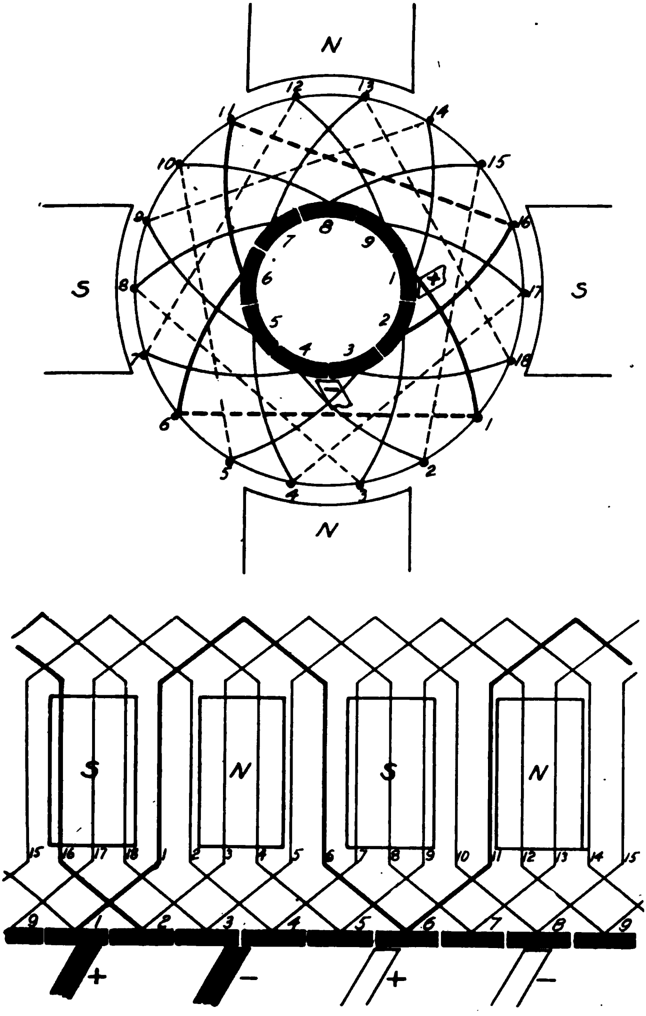


FIG. 39. SCHEME OF CONNECTIONS OF A WAVE-WOUND ARMATURE

Reviewing the fundamental equation of the dynamo as given in Chapter I the induced electromotive force, $E = FZN \div (100{,}000{,}000 \times 60)$ where F is the total number of magnetic lines of force cut, Z the number of conductors, and N the number of revolutions made per minute by each conductor.

This equation was based on the assumption that there is but one electrical path in parallel between the brushes, which is, however, not the case in commercial machines. If, then, we represent the number of such electrical paths by p and let F be equal to the product of $P/2'$ and F' where P is the number of field poles and F' the flux which enters the armature from each north pole of the field magnet, the above equation may be made to read $PF'ZN \div (2 \times p \times 100{,}000{,}000 \times 60)$.

If, therefore, as stated above, in a wave wound armature there are always two paths between the brushes regardless of the number of field poles, and in the case of a lap wound armature there are as many paths between the brushes as there are pole pieces, it is evident that a multipolar machine having a wave-wound armature $(p = 2)$ will provide a greater electromotive force than the same machine with a lap wound armature in which $p = P$. This under the assumption that the number of armature inductors remain the same in each case.

The armature shown in Fig. 38 and equipped with the lap form of winding is as may be seen fitted with 18 active inductors and 9 commutator bars, or as each winding element consists of two inductors there are as many winding segments as there are commutator segments. Starting at commutator bar 1 and tracing the course of a single element, we find this bar connected to element 1, the continuation of which connects with segment 2. This also connects with inductors 2 and 8 the latter as indicated joined to segment 3, thus illustrating the lapping of the various elements one over the other.

It will be noted that inductor 1 is connected to inductor 6; 3 is connected to 8; 5 to 10 and so on, thus indicating an interval of five between the various inductors at the rear end of the armature. In other words, this

interval or, as it is more properly termed, back pitch, is equal to five. Similarly inductor 1 is connected to segment 1 as is also inductor 4; inductors 5 and 8 are connected to segment 3 and inductors 7 and 10 to segment 4 in each case an interval of three, that is the difference between the numbers of the inductors as 1-4; 5-8; and 7-10. This interval is termed the front pitch.

Where, as in Fig. 38 the leads of each winding element connect with adjacent commutator segments, the winding is called a simple or simplex lap winding while

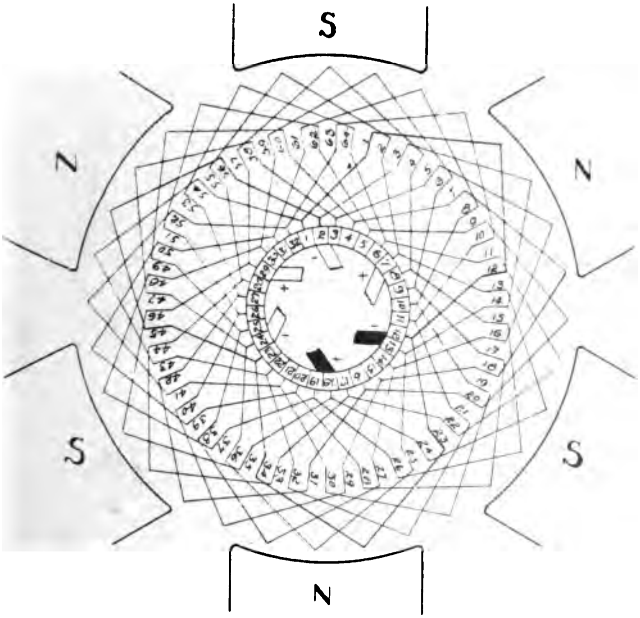


FIG. 40. TYPICAL 6-POLE DUPLEX WAVE-WOUND ARMATURE

if these leads are connected not to adjacent commutator segments, but to every other segment, the winding is referred to as a duplex lap winding. With the leads connected to every third commutator segment, the winding is said to be of the triplex lap form. The interval between the terminals of a winding element is referred to as the commutator pitch, which, in the case of the

simplex winding illustrated in Fig. 38, is 1; in a duplex winding, it would be, plus or minus 2, and in a triplex winding, plus or minus 3.

A typical wave winding is shown in Fig. 39. Tracing this diagram, we find, as in the case of the lap winding, Fig. 38, inductor 1 connected to commutator segment 1 and its continuation, inductor 6 to segment 6, the scheme being such, however, as to produce a zigzag, or as its name implies, a wave winding. Here, front and

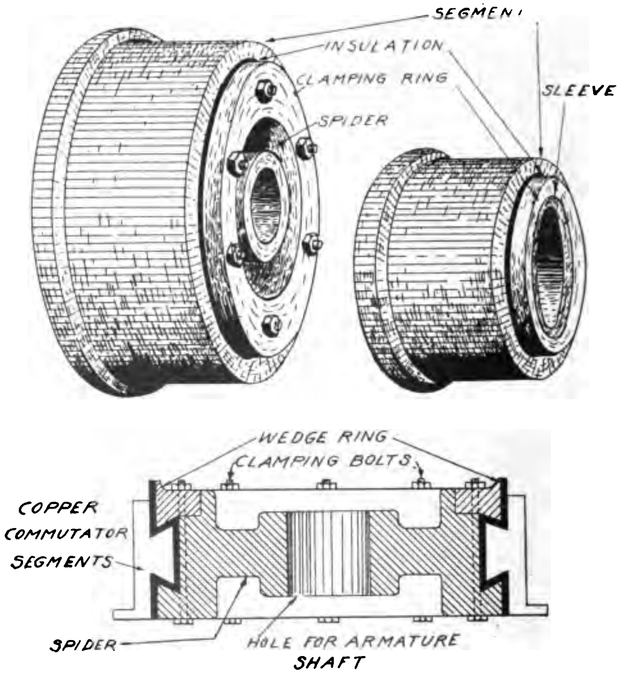


FIG. 41. TYPICAL COMMUTATOR ASSEMBLIES AND DETAILS

back pitches are each five, as is also the commutator pitch. Any wave winding which leads from a given commutator segment to an adjacent segment after passing through P ÷ 2 winding elements where P is the number of field poles for which the winding is made, is called a simplex or single wave winding. Where

P ÷ 2 winding elements lead from one commutator segment to the second adjacent, the winding is duplex and where to the third following segment, the winding is called triplex.

With duplex windings, each brush must be of such a width as at all times to bridge two commutator segments, while in a triplex winding each brush must bridge at least three commutator segments, as there will be two or three windings respectively in multiple, the object being to increase current capacity.

Multiplex windings are seldom used in modern machines; duplex windings are found only in the larger sized generators.

In the case of a simplex lap wound armature used in connection with a bipolar field, it is seen that there are two paths in parallel, between the positive and negative brushes; with a four-pole machine, there are four such paths; with a six-pole machine, six, and so on. Dividing the total number of inductors by the number of poles will therefore give the number of inductors in series in each path.

On the other hand, we find in the simplex-wave wound armature two paths in parallel between positive and negative brushes, irrespective of the number of poles and number of brush sets. Therefore, the number of inductors in series between positive and negative brushes in wave windings is always equal to one-half of the total number of inductors. Comparing lap and wave windings in which the total number of inductors remains the same, we find that the former gives considerably more paths between the brushes, and fewer inductors in series in each path, than the latter. The use of lap winding is, therefore, frequently referred to as parallel grouping of inductors, while the wave type is many times called the series grouping of inductors.

Simplex lap and simplex wave windings are also frequently termed multiple circuit and two-circuit windings, respectively.

Brushes Required

In order to permit the delivery of the greatest current output with minimum internal losses in simple or

multiplex lap windings, as many brush sets must be provided as there are pole pieces, while with the simplex wave winding two brush sets, one positive and one negative, are sufficient, although any number of sets up to and including as many as there are pole pieces, may be used.

THE COMMUTATOR

THE FUNCTION of this device has already been treated and needs no further discussion except as to its structural details. Forged copper segments thoroughly insulated one from the other by means of mica segments are mounted on and secured by means of an iron supporting member consisting as shown in Fig. 41 of a sleeve in the case of small machines, and a spider in the case of larger ones, which carry wedge rings held in place by clamping rings. Heavy layers of mica arranged in the manner indicated by the heavy black lines in the cross section prevent electrical contact between the copper segments and the iron supporting member.

Slotted projections on the inside ends of the copper segments provided means for the soldering of the coil leads.

BRUSHES

EXCEPT for special services, so-called carbon brushes are used almost exclusively on present-day dynamo machines. As a rule, brush manufacturers refrain from from making public their work, evidently preferring to keep the processes as trade secrets. Much information along this line is, however, available in a paper entitled Brushes, by W. R. Whitney, which appeared in the 1912 Journal of the Franklin Institute. Referring to the compositions of the mixtures employed, Mr. Whitney states that while these are varied to suit requirements, they are generally made up of two or more of the four elements: lampblack, finely ground petroleum coke, graphite and some kind of tar or petroleum pitch to serve as a binder. The petroleum coke is used because of its uniformity and freedom from mineral matter.

Each of these ingredients produces a different effect, and a suitable proportion seems necessary and varies

with the use of the brush. A brush made mostly of lampblack, with a suitable binder, would be dense and hard, but of poor conductivity and would cut copper rapidly. One made mostly of graphite is usually too soft and on ungrooved commutators wears away too rapidly. It can readily be appreciated that for some special purposes, it may be well to incorporate hard polishing material into a brush as where much mica must be cut and where high conductivity, and therefore much graphite, is desired.

One method of manufacture consists of kneading for several hours in a mechanical dough mixer, a finely-divided mixture of coke, lampblack and graphite to which has been added a solution of the pitch in benzol. The benzol is then driven off by heat and the dried product which is then quite hard, is reground to 200 mesh and compressed into brush form in steel molds.

Brushes have been formed by squirting bars of the mixture of the ingredients through suitable dies by means of a hydraulic press, but from reports of such processes, it is learned that the tendency of the material to flow unequally within itself during its passage through the dies appeared responsible for cleavage planes and internal curved surfaces which would often develop only after the brush was completely baked and even then could be disclosed only by breaking the brush.

After being pressed, lots of 100 to 200 brushes are packed in cast-iron boxes covered by a liberal layer of fine coke and in turn by a well-fitting cast-iron cover carrying a layer of coke dust. This box is then placed in an electrically-heated oven where the brushes are slowly baked at a high temperature.

Referring to the subject of brush manufacture, E. H. Martindale states that for the higher carrying capacities, brushes have been made up of layers of copper gauze and carbon, the former to give proper carrying capacity and the carbon to give the high contact resistance necessary to cut down short-circuit currents. In recent years, the demand for high carrying capacity brushes for slip rings of rotary converters as well as for automobile starting motors has resulted in a develop-

ment of brushes composed of a mixture of graphite and copper or some other metal, the layers of copper gauze and carbon and the mixtures of metal and graphite being pressed or molded into blocks from which the finished brush is later cut. Some of the carbon and graphite combinations are molded or pressed into blocks, while other combinations are squirted or extruded in long strips and baked to reduce the binder to carbon.

Abrasiveness of Brushes

Unequal wear of copper and mica commutator segments requires at least some abrasive to keep the mica flush with the copper and to retain a polished commutator. This is secured by means of impurities such as mica, silica, iron oxide, carborundum and quartz which are generally present, the last two being the most abrasive. With like amount of impurities, soft brushes, due to their tendency to wear more readily, are found the more abrasive.

Brush Selection

In the selection of brushes for commutators and slip rings, several important factors must be considered. Among these are, according to C. H. Smith in his paper entitled Brushes for Commutators and Slip Rings, appearing in The Electric Journal, the following:

1. The brush should possess such characteristics as will enable it to carry the maximum current to be transmitted by it. This maximum current consists of 2 factors, for either direct current or alternating current use, viz.: (a) The kilowatt load or working current of the machine, and (b) in direct-current service, the short-circuit current between the bars being commutated, and in alternating-current service, the magnetizing currents due to power factors above or below unity.

The kilowatt load or working current is readily measured or determined in terms of either direct current or alternating current, and for alternating-current service, the magnetizing, wattless or idle currents can also be definitely measured or calculated. The short-

circuit current under the brush is, however, a very indefinite factor and may have values ranging from approximately zero in a machine possessing ideal commutating characteristics to values in excess of the load or metered current in machines having poor commutating characteristics. Brushes, therefore, may be and generally are subject to loads greatly in excess of the load or kilowatt current.

Copper leaf brushes can carry 150 amp. per square inch with a drop of 0.3 v. at the contact. Carbon brushes can carry 35 w. per square inch as for example 35 amp. per square inch with a drop of 1 v. at the contact.

For sparkless commutation (a) the current density in the brush tip must not become excessive, and (b) the average amount of energy expended at the brush contact must be limited. For machines required to operate without sparking up to 25 per cent overload, a rate of energy dissipation of 35 w. per square inch may be allowed at full load, the permissible current density depending upon the voltage drop across the brush contact. The better the commutation, the more nearly uniform is the current density in the brush contact, and the higher the average density which may be allowed.

2. The brush should be homogeneous, that is, uniform in material mixture and hardness.

Commenting on this subject, Mr. Whitney states that the fracture, or appearance of the fresh surface produced by breaking the brush across its longer dimensions, discloses very effectively any irregularities produced by improper baking, or pressing. This cross section should be quite homogeneous and the fracture regularly conchoidal or square. No shelves, cracks or angular markings will be disclosed on breaking a well-made brush. It is believed that such internal irregularities represent weakened structure, that even miniature cracks might take up and carry copper from the commutator, and that breaking of a brush in use may often be attributed to internal cracks produced in the manufacture.

3. Brushes for either alternating or direct current

should be self lubricating; some operators, however, equip their machines with alternate sets of self-lubricating and non-lubricating brushes depending upon the former to supply whatever lubrication may be required by the latter.

4. For under-cut commutators, the brush material should be entirely, or nearly, free of abrasive material or the commutator will wear unduly fast, bridge the slots, necessitate frequent beveling of the bars, repeated undercutting and constant cleaning.

5. For smooth commutators with soft mica, a larger percentage of abrasion is desirable than in brushes for undercut mica.

6. For smooth commutators with soft mica, brushes should be highly abrasive. This usually means a decreased brush capacity and decreased lubricating values, although it is claimed for some brushes that proper abrasive effect is secured by hardening under enormous pressure, no abrasive material being used.

7. For alternating current slip rings, the brushes should be as nearly self-lubricating as possible and should themselves wear rather than wear or cut the rings. These brushes may be of metal, graphite composition or of a graphitic nature only. If of metal-graphite, they should not wear so as to form a continuous "fringe" or "wire edge" along the sides of the brushes at the rings, but should be of a mixture sufficiently granular to disintegrate or break away in small particles.

Continuing, Mr. Smith informs us that to a limited degree, at least, the characteristics of a brush are indicated by the degree of its hardness. Exceedingly hard brushes generally carry a large amount of abrasive and have a low current density or carrying capacity, while the softer ones possess but a small amount of abrasive, are highly graphitic and have a high current density. For high-speed electrical machines such as turbo-generators and high-speed rotary converters, it is at times of advantage to employ brushes of a rather low density because they tend to maintain a more intimate contact with the commutator than brushes of high density. A

dense graphite brush of high conductivity has by experience been found to be especially suitable for steel and cast-iron slip-rings, while soft graphitic brushes of high conductivity are recommended for low-voltage generators and boosters.

Brush Tension

Proper brush tension is of considerable importance in the operation of dynamo electric machinery, especially when working the brushes at a high current

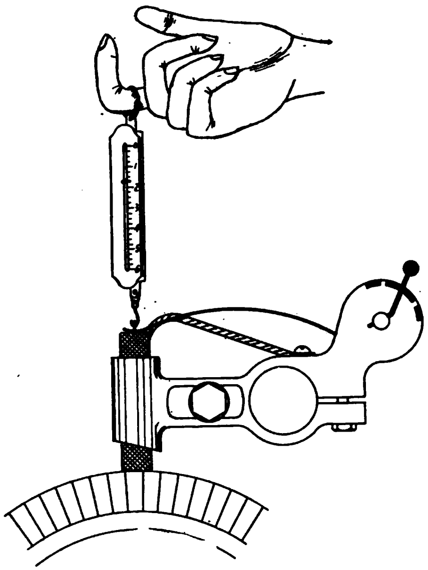


FIG. 42. A SMALL SPRING SCALE ARRANGED IN THIS MANNER WILL READILY INDICATE THE BRUSH PRESSURE

density. If the pressure is not equal on all brushes, the load will not be divided equally among them, and overheating will occur with detrimental results.

Brush tension may range from a minimum of 2 lb. per square inch to a maximum of 5 lb. per square inch, depending upon the characteristics of the brush, the speed of the commutator and its mechanical condition.

Generally, however, tensions of 2.5 to 3.5 lb. per square inch are used on commutators and 3 to 5 lb. per square inch of slip rings, with the exception of crane, hoist and railway motors, for which tensions of from 4 to 7 lb. are recommended.

Experienced operators can frequently determine the tension or pressure with which the brush bears against the commutator by slightly raising the brush in the brush holder. It is, however, preferable, especially for the inexperienced man, to determine this tension by

FIG 43. BOX TYPE BRUSH HOLDER

means of a small spring scale in the manner indicated in Fig. 42. In making these determinations, care should be exercised to see that the brushes work freely in their holders and unless the angle of pull is the same on each brush the results will differ.

A tension in excess of that actually required should not be employed, as doing so increases unnecessarily the coefficient of friction between the brushes and the commutator, which in turn results in energy losses of values not ordinarily realized.

The number of watts loss in any given machine due to brush friction may be readily determined by means

of the following formula given by E. H. Martindale in a recent issue of the Electrical Review:

$$W = \frac{A \times P \times F \times S}{44.26}$$

where W is the loss in watts, A is the total area of brush contact in square inches, P is the brush pressure in pounds per square inch, F is the coefficient of friction

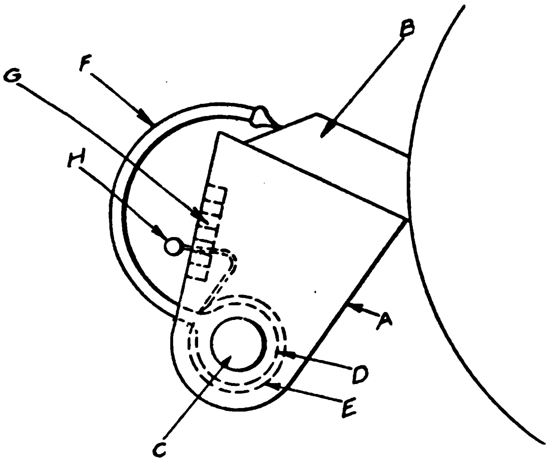


FIG. 44. REACTION TYPE BRUSH HOLDER

of the brush, S is the peripheral speed of the commutator expressed in feet per minute and 44.26 is the number of foot pounds equivalent to one watt.

The coefficient of friction of a carbon brush, as defined by Mr. Martindale, is the ratio of the frictional pull of the commutator on the brush to the pressure of the brush on the commutator and varies from a little above zero to over 0.9.

Brush Holders

WHILE IN DETAIL brush holders employed in connection with present-day electrical machinery may vary to some extent, the box and reaction types such as shown in Figs. 43 and 44, respectively, are now used almost

exclusively. In the former, the brush is carried in a slot and a helical spring acts through a finger arm to hold the brush firmly against the commutator in such a manner as to permit movement of the brush parallel

FIG. 45. BOX TYPE BRUSH HOLDER FOR USE IN CONNECTION WITH COLLECTOR RINGS

to the face of the holder only. This insures the brush readily following any irregularity in the commutator and prevents chattering. Adjustment of the brush pressure is accomplished by means of a series of notches on

FIG. 46. APPLICATION OF BOX TYPE BRUSH HOLDER FOR USE IN CONNECTION WITH COLLECTOR RINGS

the body of the holder by which the spring tension may be varied.

A brush holder for use in connection with collector rings is shown in Fig. 45.

In the reaction type of holder, Fig. 44, brush B is pressed tightly against the holder, A, by the lever, F; this lever is given tension by a coiled spring, E, about a sleeve, D, which moves freely on the brush holder stem, C. G is a series of notches for receiving the spring projection, H, by means of which the spring tension is governed.

Proper and sparkless operation of dynamos requires equal spacing of the brush holders. In order to do this, take a piece of paper several inches wide and of the same length as the circumference of the commutator and measure and mark it into the same number of equal spaces as there are brush holders. Then by placing the paper around the commutator under the brushes and shifting the brush arms so that the toe or heel of each set of brushes will come to its respective mark on the paper, the brushes are equally spaced. This may be done in a few minutes time and the paper laid away for future checking up of the adjustments if the diameter of the commutator has not been altered by excessive wear or turning down.

Another way to check up this adjustment is to prick punch the ends of the commutator bars under one edge of each set of brushes after they have been correctly spaced. To check, bring the punch mark to one set of brushes and then see whether all the other brushes coincide with their punch marks on the ends of the commutator bars.

Questions on Chapter VI

1. Why are armature cores laminated?
2. When a coil is short circuited by the brush, why does it not set up a heavy current?
3. What determines the spread of a coil on a drum armature?
4. How many paths would current have in an 8-pole machine with lap-wound armature? With wave wound?
5. If the 8-pole dynamo armature has 640 inductors, how many would be in series for a lap winding? How many for a wave winding? (80; 320.)

6. At 1200 r.p.m. what voltage would the lap-wound armature of question 5 develop, F′ being 1,750,000? What voltage the wave winding? (112; 448.)
7. Draw a lap winding for a 4-pole dynamo with 16 conductors and 8 bars; front pitch, 5; back pitch = 3.
8. Draw a wave winding for a dynamo with 4 poles, 22 conductors, 11 bars, front and back pitch 5.
9. Why is a commutator used?
10. How many sets of brushes are used for a wave winding? For a lap winding?
11. How is the commutator insulated?
12. If mica showed high on a commutator, what change in brushes would you suggest?
13. What area of contact is needed for carbon brushes to carry 200 amperes? (5 sq. in.)
14. If a commutator is 12 in. diameter, runs at 1500 r.p.m., has brushes with a total contact area of 20 sq. in. and pressure of 3 lb. per sq. in ; with F =.05 what will be the loss from brush friction? (3200 watts.)
15. How would you test for correct brush spacing? For correct tension?

CHAPTER VII

DIRECT-CURRENT GENERATORS

LOSSES AND EFFICIENCIES; INSPECTION TESTS AND REGULATION

IN all dynamo electric machinery, various losses exist which, as may be expected, have a direct bearing upon the efficiency of the machine, and while some of these losses are dependent in magnitude upon factors of design and construction, others not possible of entire elimination may, to a great extent, be materially reduced

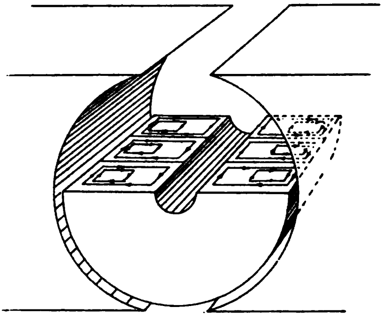


FIG. 47. SHOWING ISOLATION OF EDDY CURRENTS WITHIN INDIVIDUAL LAMINATIONS

by proper operation. There are three distinct kinds of losses—the iron or magnetic losses, the copper losses and the purely mechanical losses such as are found in any kind of mechanism.

The iron losses are capable of further subdivision as eddy current losses and hysteresis losses. When a mass of iron such as the core of an armature is rotated so as to cut rapidly, or be cut by magnetic lines of force, an electromotive force is induced which sets up, or tends to set up, local currents generally referred to as eddy currents. The existence of these always involves a loss which in the aggregate may be considerable and as a

consequence modern machines are fitted with laminated armatures, and in some instances laminated pole pieces, by means of which the losses from this source may be reduced to a minimum. As already explained in Chapter VI, in direct-current machines of moderate size, the armature core is subject to from 15 to 60 or more cycles per second, and the laminations which are insulated one from another by means of insulating varnish or rust, are usually made from 0.020 to 0.035 in. in thickness.

Flow of eddy currents in the case of an armature is in a direction parallel to the axis of the shaft so that by the use of a laminated structure the currents are confined to the individual laminations, thus reducing them to a minimum. It is obvious, therefore, that the thinner the laminations, the less the eddy current losses.

A formula suitable for the determination of eddy current loss in any given machine is the followng:

$$We = j\,V\,(t \times f \times B)^2 \div 1{,}000{,}000$$

Where We is the eddy current loss in watts; j is a coefficient, the value of which depends upon the kind and quality of metal; V is the volume in cubic inches of the structure in which the eddy currents occur; t is the thickness of the sheets in inches; f is the frequency in cycles per second, and B is the maximum flux density in lines per square inch.

For ordinary sheet steel j has an average value of 0.000,022 while for silicon sheet steel its value varies from 0.000,043 to 0.000,098 with an average of 0.000,065.

Hysteresis Losses

As the core of an armature revolves between the pole pieces, it is alternately magnetized in one direction, demagnetized, magnetized in the opposite direction. Due, however, to a peculiar property of iron, the magnetization lags behind the magnetizing force and as a consequence the magnetization for equal magnetizing forces rising and falling will not be the same. This property or action is termed hysteresis, meaning "to lag behind," and results in a loss of energy dissipated in the form of heat.

Figure 48 shows a typical hysteresis curve of a piece of wrought iron, or the resulting magnetization when the magnetizing force is varied. As indicated at point A, the particular piece of wrought iron evidently possessed a given amount of residual magnetism, approximately 4500 lines; as the number of ampere-turns per unit length is increased, the magnetic flux per unit sec-

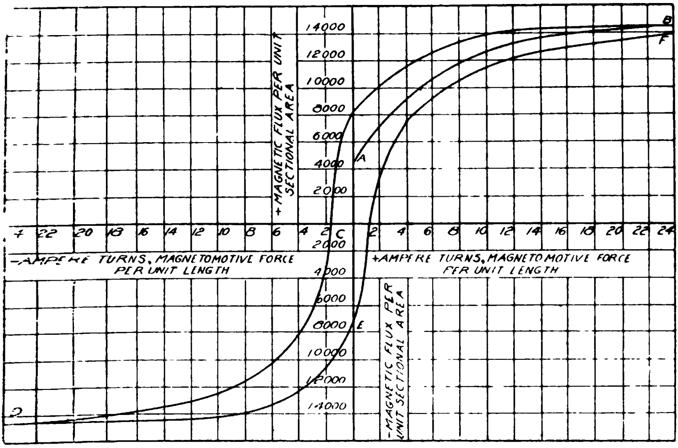


FIG. 48. TYPICAL HYSTERESIS CURVE

tional area increases as represented by the portion AB of the curve; but with a decrease in magnetomotive force or number of ampere-turns per unit length, the decrease in magnetism will not be according to AB, but rather along curve BC, thus showing that even when the value of the magnetomotive force has dropped to zero, and is already approaching –2 ampere-turns, that is, has already been reversed, the direction of the magnetic flux is still positive. Further increase in magnetomotive force, however, produces an increase in magnetism in the opposite sense as indicated by curve CD.

Again, upon reversal of the magnetomotive force, the magnetism lags as shown by DE and as in the first reversal, the direction of the magnetic flux does not change until nearly + 2 ampere-turns have become effective. The remaining portion of the cycle is as indicated by EF.

This series of changes is what occurs within the core of an armature and the harder the iron, the greater is the enclosed area; or, in other words, the harder the iron, the greater the hysteresis loss. For steel the area enclosed within the curve would be considerably more than that for wrought iron, thus indicating that the former is subject to greater hysteresis losses than the latter.

For any cycle, the hysteresis loss varies according to the range of flux density during that cycle. For all practical purposes and with a flux density ranging from ± 2000 to $\pm 12{,}000$, the hysteresis loss per cycle may, according to Steinmetz, be obtained by the following formula:

$$E = 0.83\, n\, VB^{1.6}$$

where E is the loss of energy in ergs* per cycle, n is a constant coefficient, the value of which for various materials is given in the table below. V is the volume of the iron in cubic inches and B is the range of flux density during the cycle, in lines per sq. in.

Values of n for various materials:

Best quality of sheet iron, annealed	0.0030
Ordinary sheet iron, annealed	0.0040
Soft annealed cast iron	0.0080
Soft machine steel	0.0095
Cast steel	0.0120
Cast iron	0.0160
Hardened steel	0.0250

With f number of cycles per second, the hysteresis power loss is equal to

$$Wh = (0.83\, nf\, VB^{1.6}) \div 10{,}000{,}000$$

where Wh is the loss of power in watts.

Copper Losses

As the power loss in watts in any electric conductor is equal to the product of the number of ohms resistance in that conductor and the square of the current flow in amperes, so is the power loss in watts in any armature equal to $R_0\, I_0^2$ where R_0 is the hot resistance of the armature winding (including the contact resistance of

* The erg is equal to 1/100,000,000 joules; the joule is the practical unit of electrical energy and is produced when a steady current of 1 amp. passes through a resistance of 1 ohm for 1 sec.

the brushes and the resistance of the brushes themselves) and I_0 is the rate of current flow expressed in amperes.

In determining the resistance of the armature circuit, this must be taken across the two brush terminals with the brushes in place as when the machine is in operation, that is, the resistance between the positive and negative armature terminals.

The shunt excitation loss is dependent upon the terminal electromotive force and the current flow through the winding. It is equal to E_1I_1, where E_1 is the electromotive force applied across the terminals of the circuit and I_1 is the value of the shunt field current in amperes. In a generator about 20 per cent of this loss will be in the shunt field rheostat.

To determine the series field loss the same formula employed to determine the armature loss may be used except that I is the current flow in amperes through the series winding and R is the resistance of the winding.

Mechanical Losses

These are made up of the bearing friction losses, the brush friction losses, and the windage losses. For moderate speed bearings with ring lubrication and light machine oil, the friction loss for each bearing may be approximately determined by multiplying the product of 0.8 of the bearing diameter in inches and the bearing length in inches by the result obtained in raising to the ⅔ power the quotient of the rubbing velocity in feet per minute divided by 100.

Assuming the coefficient of brush friction to be equal to 0.28 and the brush pressure 2 lb. per square inch, the brush friction loss in watts may be determined by means of the following formula:

$$Wb = 1.25\ AS \div 100$$

where A is the total brush rubbing surface in square inches, and S is the rubbing velocity in feet per minute.

The windage loss can not be accurately calculated and, with peripheral velocities less than 6000 ft. per minute is so small that it may be neglected.

Determination of Losses

As in practice eddy current, hysteresis, friction and windage losses cannot, with any degree of accuracy, be determined separately, it is usual to refer to these losses combined as stray power losses. These, with constant speed and field excitation, remain practically fixed for all values of machine output so that in the case of shunt-wound generators operating at constant speed and with unvarying field current the stray power losses may

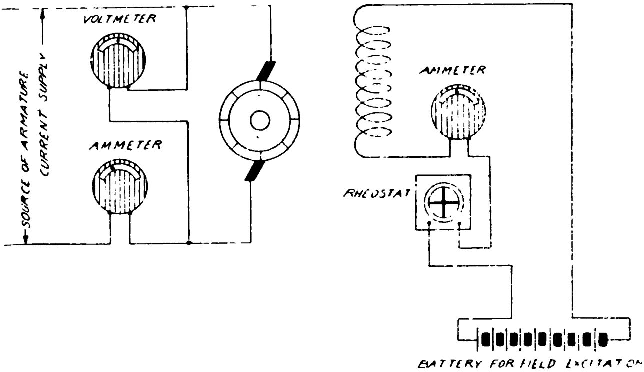


FIG. 49. DIAGRAM OF CONNECTIONS EMPLOYED WHEN DETERMINING GENERATOR STRAY POWER LOSSES

be assumed constant under all conditions of load; but, due to the variation of field excitation with variation of load in series-wound machines, this does not hold for such generators.

To determine the stray power loss of any generator at a prescribed speed and a prescribed degree of field excitation, run the machine as a motor employing the scheme of connections shown in Fig. 49. The field should preferably be separately excited, the ammeter and rheostat shown being provided for the purpose of maintaining a check on and regulating this. The voltmeter connected across the brushes and the ammeter inserted in the armature circuit allow observation of armature current I_0 and applied electromotive force E.

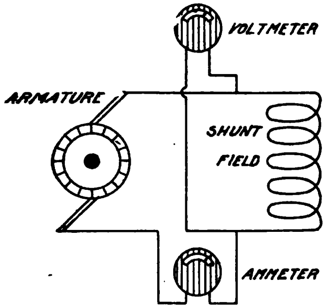
Inasmuch as the machine is driven as a motor without load, all of the power $E\,I_0$, which is delivered to the armature is utilized to supply the stray power loss S and to overcome the armature loss $R_0\,I_0^2$, where R_0 is the resistance in ohms of the armature windings. Or,

$$E\,I_0 = S + R_0\,I_0^2$$

from which,

$$\begin{aligned} S &= E\,I_0 - R_0\,I_0^2 \\ &= I_0\,(E - R_0\,I_0) \end{aligned}$$

For small variations of speed and field excitation, it is safe to assume a variation of stray power loss pro-



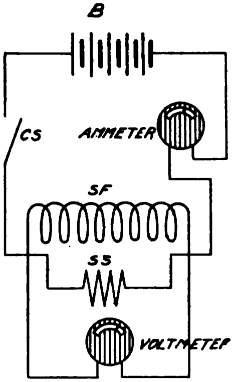


FIG. 50. CONNECTIONS EMPLOYED IN DETERMINING SHUNT FIELD LOSSES

FIG. 51. INSTRUMENT CONNECTIONS USED TO DETERMINE RESISTANCE OF SERIES FIELD AND SHUNT

portional to the armature electromotive force so that for any other value of E as E^1 we have

$$S^1 = S\,\frac{E^1}{E}$$

where S^1 is the value of the stray power loss with voltage at E^1.

Field and Armature Losses

By inserting a low-reading ammeter in the shunt circuit and connecting a voltmeter across the terminals of that circuit in the manner indicated in Fig. 50, the

shunt field excitation loss expressed in watts may be obtained from the product of the instantaneous volt and ammeter readings.

Generally, as already explained, the series field of a compound-wound generator is fitted with a series shunt in order to provide a means for adjusting the degree of compounding. The series excitation loss is therefore equal to the product of the square of the current delivered by the machine and the combined parallel resistance of the series coil and series shunt.

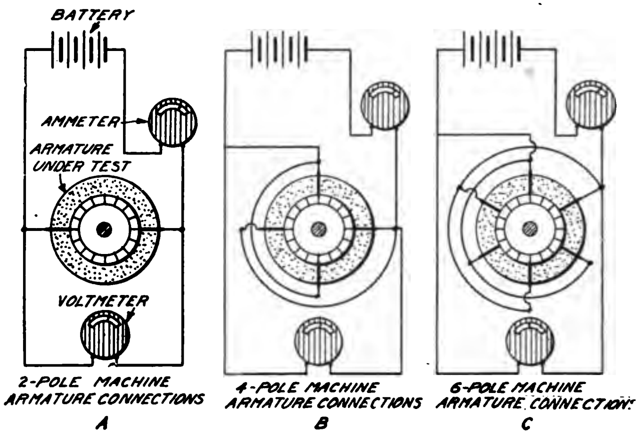


FIG. 52. SCHEME OF CONNECTIONS EMPLOYED IN MEASUREMENTS OF ARMATURE RESISTANCE

If the resistance of this is not known, it may be quite readily obtained by employing a Wheatstone bridge or if such an instrument is not available, the voltmeter ammeter method will prove satisfactory. Use the scheme of connections indicated in Fig. 51, where SF and SS are the series field and series shunt respectively under test, B a low-voltage battery and CS the control switch. Upon closing the switch a flow of current is established, the rate of which is as indicated by the ammeter, while the reading of the voltmeter indicates the voltage applied across the terminals of the series field and its shunt. The resistance in ohms, of the circuit under test will

then be equal to the quotient obtained by dividing the voltmeter reading by that of the ammeter.

To determine the copper losses occurring in an armature, it is necessary to determine, first, the resistance of the armature circuit, which in the case of a two-pole machine may be done by the volt-ammeter method with the scheme of connections shown at A, Fig. 52. With a low-voltage current flowing through the armature, note the reading of the instruments and calculate the resistance of the armature winding by dividing the number of volts indicated by the reading of the ammeter.

In the case of a four-pole machine, use the scheme of connection indicated at B, Fig. 52, and when a six-pole machine armature is under test, employ the connections shown at C, care being taken, however, to see that the brush contacts are properly placed. Where the armature is that of a two-pole machine, place the brush contacts diametrically opposite one another, while in the case of a four-pole generator armature, these will have to be placed on the quarter; in a like manner, six- and eight-pole machine armatures will require placing the test leads 60 and 45 deg. apart, respectively.

With the instrument leads connected to the brush holders, accurate results will not be obtained, due to the voltage drop caused by brush and brush contact resistance, which may be from 1 to 2 v. unless the brushes are well fitted to the commutator and the brush holders.

Knowing the value of the resistance of the armature circuit, the loss in watts occurring under any given load may be readily calculated by multiplying this resistance by the square of the number of amperes current flowing.

Measurement of Input

Where the driving unit is a steam or internal combustion engine of the reciprocating type, the amount of energy delivered to the generator may readily be determined from indicator cards. By taking a card first with the set running unloaded, and then another under load, calculating the number of horsepower developed in each case and taking the difference, we secure the total number of effective horsepower. To reduce this to kilowatts,

multiply by 746 and divide the product thus obtained by 1000.

The indicated horsepower of a reciprocating steam engine is obtained by dividing the product of the number of pounds of mean effective pressure, the length of stroke in feet, the area of piston in square inches and the number of strokes per minute, by 33,000, the various factors involved, except the mean effective pressure, being secured by measurement and count. By employment of the method of ordinates or the use of a planimeter, the

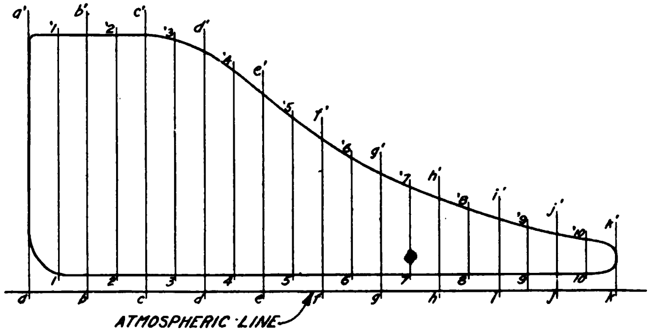


FIG. 53. THE AVERAGE LENGTH OF THE NUMERICALLY DESIGNATED ORDINATES WHEN MULTIPLIED BY THE SCALE OF SPRING USED WILL GIVE THE MEAN EFFECTIVE PRESSURE

mean effective pressure may be readily obtaind from the indicator cards.

To use the method of ordinates, erect a series of equally spaced ordinates perpendicular to the atmospheric lines, as indicated by aa′, bb′, cc′, etc., in Fig. 53. Midway between these erect a second set of ordinates as 1′1, 2′2, 3′3, etc. The average of the sums of the lengths of these numerically designated ordinates measured in inches and multiplied by the scale of spring employed will give, as a product, the mean effective pressure in pounds per square inch.

If the machine is of the belted type, the number of horsepower transmitted by the belt is approximately obtained by dividing the product of the velocity of the belt, in feet per minute, and the width of the belt, in inches,

by 550. As in the foregoing instance, this may be reduced to kilowatts by further multiplication by 746 and dividing the result by 1000.

OUTPUT

ALTHOUGH THE OUTPUT of a generator can be calculated from the ammeter and voltmeter readings (and in the case of alternating-current work, power factor meter readings) more accurate results may be had by the em-

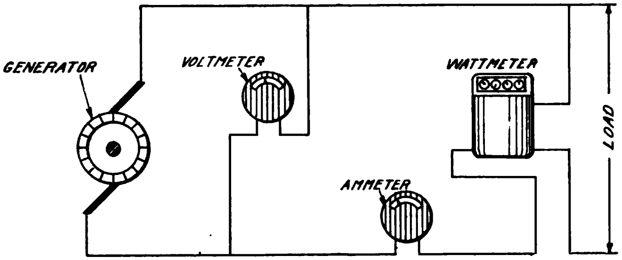


FIG. 54. INSTRUMENT CONNECTIONS USED FOR CHECKING OUTPUT OF DIRECT CURRENT

ployment of properly calibrated wattmeters and under variable load conditions, watthour meters.

Voltmeter, ammeter and wattmeter (or watthour meter) connections for output measurements of a two-wire direct-current generator are shown in Fig. 54; with properly calibrated instruments, the product of the instantaneous readings of the voltmeter and the ammeter should correspond with that of the wattmeter.

EFFICIENCY

THE EFFICIENCY of an electric generator like that of any machine may be defined as the ratio between the output and the input, ordinarily expressed in per cent. This efficiency, known as the true or mechanical efficiency, may be represented by the following equation:

$$\text{Mechanical Efficiency} = \frac{\text{power output}}{\text{power input}}$$

$$= \frac{\text{power output}}{\text{power output} + \text{losses}}$$

Therefore, knowing the output and having determined the various losses by means of the methods described above, the mechanical efficiency of any generator can, by the application of the formula, be quite readily determined.

Let us take for example a series-wound machine delivering 50 amp. at 110 v. and which we have found has a stray power loss of 700 w.; the resistance of the armature when hot is 0.15 ohms and that of the series windin 0.12 ohms. Both armature and series coil losses are straight RI^2 losses, so that for the armature we have:

Armature loss $= R_0 I_0^2 = 0.15 \times 50^2 = 375$ w.

Series field $= R_1 I_1^2 = 0.12 \times 50^2 = 300$ w.

The output is equal to $50 \times 110 = 5500$ w.

The efficiency then is equal to 5500 divided by $(5500 + 375 + 300 + 700)$ or 0.80, or 80 per cent.

In the case of a shunt-wound generator delivering a like amount of current at the same voltage and with armature resistance and stray power loss the same as in the case of the series machine cited above, we also have an output of 50 times 110 or 5500 w.

Let us assume, however, that the resistance of the shunt field winding, including that portion of the rheostat necessarily cut into service, to be 44 ohms. The current flow through this part of the machine is then equal to the applied voltage, or 110 divided by the resistance or 44, which is equal to 2.5 amp. The shunt field loss is then equal to the product of 110 and 2.5 or 275 w.

In calculating the armature loss, account must be taken not only of the current delivered by the machine, but also that used for field excitation purposes or, in other words, the total armature current, which is 50 plus 2.5 or 52.5 amp. Multiplying the square of this, or 2756.25, by the resistance of the armature winding, or 0.15 ohms, we obtain 413.4, or let us say 413 w. We have therefore the efficiency of this machine equal to

$$\frac{5500}{5500 + 275 + 413 + 700} \text{ or } 0.80 = 80 \text{ per cent.}$$

In calculating the efficiency of a compound-wound generator, account must be taken of the scheme of con-

nection employed; that is, whether of the short shunt or long shunt type. Let us consider a short shunt compound-wound machine, delivering 100 amp. at 220 v. and having a shunt field resistance of 110 ohms, a series field resistance of 0.04 ohms, an armature resistance of 0.28 ohms, and a stray power loss of 1000 w.

The shunt field loss may be obtained by multiplying the resistance of this winding in ohms, 110, by the square of the current, which is equal to the applied voltage divided by the resistance. The applied voltage is, however, not 220, the terminal voltage, but is equal to the terminal voltage plus the drop through the series winding; that is, the product of the resistance of the series winding, 0.04 ohms, and the current, or 100 amp.; that is, 4 volts. We have therefore applied to the terminals of the shunt winding an electromotive force of 220 plus 4, or 224 v.

Dividing 224 by 110, we have as a value for the shunt field current 2.04 amp. Squaring this and multiplying by the resistance of the winding, 110 ohms, a product of 457 is obtained as the number of watts loss in the shunt field.

The series field loss is equal to the resistance, 0.04 ohms, times the current 100 squared, or 400 w., while the armature loss is equal to 0.28 ohms, the resistance of the armature winding times the square of the total current $(100 + 2.04)$, or 2915.4 w.

The efficiency of this machine is then:

$$E = \frac{100 \times 220}{100 \times 220 + 457 + 400 + 2915.4 + 1000} = 0.821 = 82.1 \text{ per cent.}$$

In any electric generator, the useful energy, that is the energy capable of being utilized for purposes other than in the machine itself, is somewhat less than the energy generated or the product of the armature current and the brush electromotive force. If we represent this energy by E_0I_0 and that available for external use by E_1I_1, we may employ the following relation, $E_1I_1 \div E_0I_0$, to indicate the electrical efficiency of the machine.

Average efficiencies of generators of various capac-

ities are as shown in Fig. 55. A curve for any machine at different loads may be obtained by plotting the efficiencies at various loads, the per cent efficiency for each point being secured in the manner stated above.

Regulation

Voltage regulation of a generator which is the percentage of the full-load terminal electromotive force by which the terminal electromotive force decreases from

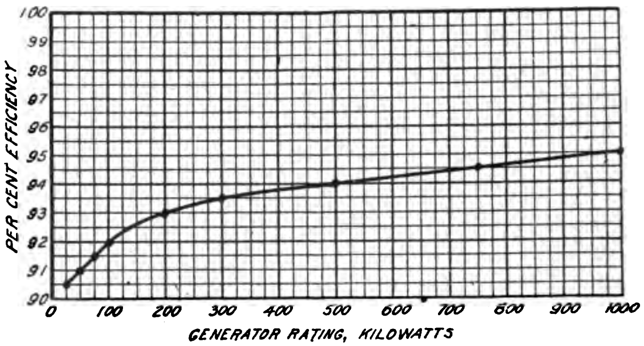


FIG. 55. VARIATION OF AVERAGE EFFICIENCY OF GENERATORS WITH RATED OUTPUT

no load to full load, varies not only with the type of generator but also to some extent according to the inherent characteristics of the individual machine. It may be obtained by dividing the difference between the full-load voltage and the no-load voltage, by the full-load voltage, the voltage readings being taken with the speed of the machine constant.

Assume a machine having a no-load voltage of 110 and a full-load voltage of 100; its regulation would then be equal to the difference between 110 and 100, divided by 100, or 10 per cent.

Except in power service where a considerable drop in voltage results in a heavy current demand, voltage regulation has practically no effect upon the efficiency of a generator.

INSPECTION

IT IS IMPORTANT TO SEE that the bearings and journals of dynamo electric machines are in good mechanical condition, in proper alinement and so adjusted as to provide a uniform air gap at all points along the periphery of the revolving member. A wooden wedge of the form shown in Fig. 56 and graduated in the manner indicated will prove extremely useful in the checking up of air gap widths.

When starting a new machine, or one having been out of service for some time, remove the top bearing caps

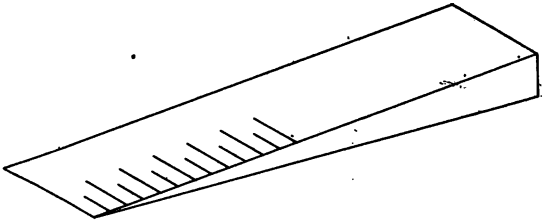


FIG. 56. GAGE FOR CHECKING AIR GAP

and raise the rotor or armature sufficiently high to give access to all parts of the shaft and lower half of the bearing. After cleaning well with a piece of cloth saturated with kerosene, carefully wipe these parts so as to remove all traces of dirt, grime or other substances which may have a tendency to cause heating.

If the oil well contains old or dirty oil, remove this and fill with clean kerosene to such height as will bring the surface of the kerosene in contact with the oil rings. After a half hour or more, remove the kerosene and wipe the well out thoroughly.

Use only a high grade of oil, and when filling the well pass the oil through a strainer, bringing it up to such a height as will insure a copious supply to the shaft, with the rings working properly.

Heating may be generally attributed to any of the following causes: (a) sticking of oil rings; (b) excessive belt tension; (c) rough bearing surface; (d) improper

alinement of bearings or fitting of journal boxes; (e) lack of end play.

In the event of heating, feed the bearing an abundant supply of heavy oil, loosen the top bearing caps and, if belt driven, slacken the belt. Should the heating under this treatment not subside, shut down, care being taken, however, to prevent "freezing" by keeping the machine running slowly until the shaft is cool.

Frequent inspection of the bearings is advisable, especially in the case of high-speed machines.

Brushes and Commutator

To prevent "grooving" of the commutator, the brushes of one set should always be placed in a position staggered to those of the set following, and to insure proper commutation, the various sets of brushes must be spaced equidistant about the periphery of the commutator.

To provide proper contact surface between the brushes and the commutator, insert a strip of sandpaper, with the rough side toward the brush face, between the brush and the commutator, and with the brush in position, draw the sandpaper in the direction of rotation, repeating this as often as necessary to secure a smooth face; do not allow the sandpaper to come in contact with the brush during the return strokes.

Commutators, at all times, must be maintained as smooth as possible, and if unduly worn so as to cause excessive sparking, turning down should be resorted to. After this has been done and the entire surface given a smooth finish, the commutator should, within a short time, provided it is receiving the proper care, acquire a highly polished surface.

High mica is a common source of sparking, but may be avoided by undercutting.

Connections and Windings

Each time the machine is shut down, all accessible binding posts and connections should be carefully examined and tried out and if found loose, should be tightened or resoldered, as the case may be. The wind-

ings ought likewise be looked over and, if dirty, should be blown out and wiped off.

Questions on Chapter VII

1. Enumerate the various losses existing in any dynamo electric machine.
2. What are the stray power losses of a generator and how would you determine them?
3. How will increasing the flux density affect the eddy current loss? The hysteresis loss?
4. What effect will increasing the armature speed have on each of those losses?
5. What effect will running at a higher voltage have on the shunt field loss?
6. From the problems given, which is greater, the field loss or the armature loss?
7. What effect will high armature resistance have on efficiency?
8. Calculate the efficiency of the 220-v. generator, considering it as a long shunt connection. (Shunt current will flow through the series coils.) (82.3%.)
9. A short-shunt compound-wound machine is delivering 400 amp. at 110 v.; if the stray power loss amounts to 1500 w. and the shunt field winding has a resistance of 55 ohms, the series field a resistance of 0.02 ohms and the armature a resistance of 0.026 ohms, what is the efficiency of the machine? (82.8%).

CHAPTER VIII

VOLTAGE CONTROL OF D.C. GENERATORS

METHODS AND APPARATUS FOR MANUAL REGULATION; AUTOMATIC REGULATION

ELECTRICITY, like air, water, steam, etc., is of service to man only when under proper control. The flow of electric current in circuits supplied by so-called constant-potential generators is dependent upon the resistance of the circuit and the requirements of the consuming devices, and is limited only by the capacity of the generators, although circuit-breaking devices should be provided to prevent damage to the machine due to possible overloads. Except within specified limits dependent upon service requirements, generator terminal voltage must vary but little and as each variation in prime-mover speed, machine load and winding temperature results in a proportional variation in terminal voltage, it is imperative that some form of control be employed.

Maintenance of proper voltage is of vital importance to the life of incandescent lamps. Operating them above rated voltage will, of course, increase the candlepower and decrease the watts consumption per candlepower, a fact which may at first thought appear advantageous. This, however, is not always the case, as may be seen by referring to the curves in Fig. 57, showing the relation between the life and candlepower of incandescent lamps operating under different percentages of rated voltage. With the voltage increased 2 per cent above normal, the candlepower will be increased about 12 per cent, but the life of the lamp will be but 67 per cent of that which it would be under proper voltage; decreasing the voltage 2 per cent below normal increases the life of the lamp 50 per cent, and decreases the candlepower 11 per cent.

Referring to the fundamental equation of the direct-current dynamo, we find the generated voltage to be

directly proportional to the number of field magnet poles, the density of the magnetic flux, the number of outside armature conductors and the speed of the armature. The first and third of these factors are fixed and as the speed variation under normal conditions of operation

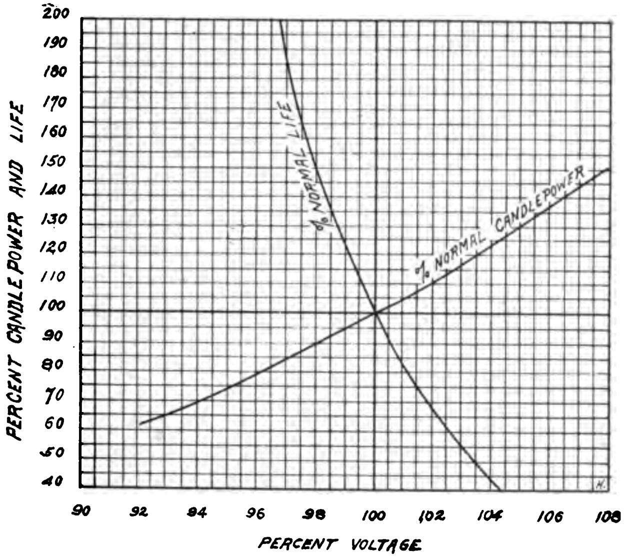


FIG. 57. RELATION BETWEEN OPERATING VOLTAGE AND RESULTANT LIFE AND CANDLEPOWER OF INCANDESCENT LAMPS

is negligible, it is at once apparent that the terminal voltage may be most readily controlled by means of varying the density of the magnetic flux. And as this in turn is dependent upon the degree of field excitation, any means by which the current flow in the field windings may be controlled will also act as a control of the machine voltage. Inserting some form of variable resistance in the circuit supplying current to the field winding will, therefore, allow the desired result to be realized. Any such resistance is generally known as the field rheostat.

Characteristic generator curves indicate the degree of variation of terminal voltage with increasing output

and the necessity of employing a field rheostat. Even in the case of the flat compound-wound generator, which by its very design is supposed to maintain a practically constant terminal voltage, the use of the rheostat in the shunt-field circuit is indispensable.

Reviewing the development of dynamo electric machines, we find that while the majority of these generators employed field rhetostats, the voltage of many of them was controlled by varying the length of the air gap; the underlying principle was, however, the same, namely, the variation of the effective magnetic flux. These rheostats which were employed, exemplified by the ones used in connection with the Thomson-Houston system, consisted of a nest of asbestos tubes encased in a well-ventilated iron box and having closely wound upon them German-silver resistance wire. The taps along the circuit of this resistance were connected to a set of contacts arranged in the form of a circle on the marble or slate face plate of the containing case. The desired resistance was cut in or out in the same manner as is done in present-day manually-operated rheostats by means of a hand wheel attached to a contact arm connecting the resistance to one side of the supply circuit.

Except in the smaller sizes and those employed for special purposes this form of rheostat is no longer used, the heavier current now required to excite the large modern generator and the greater degree of safety and reliability demanded by operators having called for somewhat different designs. For moderate-size machines up to about 1500 kw., plate rheostats are generally employed. These consist of plates composed of a base of insulating material to which is attached the resistance wire or ribbon, contacts and lever, the whole being carried by a japanned iron case; in others the resistance material is attached to a plate of porcelain-covered cast iron by means of a coating of fused enamel or cement. Any number of these units may be bolted together and electrically connected in multiple to meet specific requirements.

Field rheostats used in conjunction with large generators are usually of the box type, having resistance in

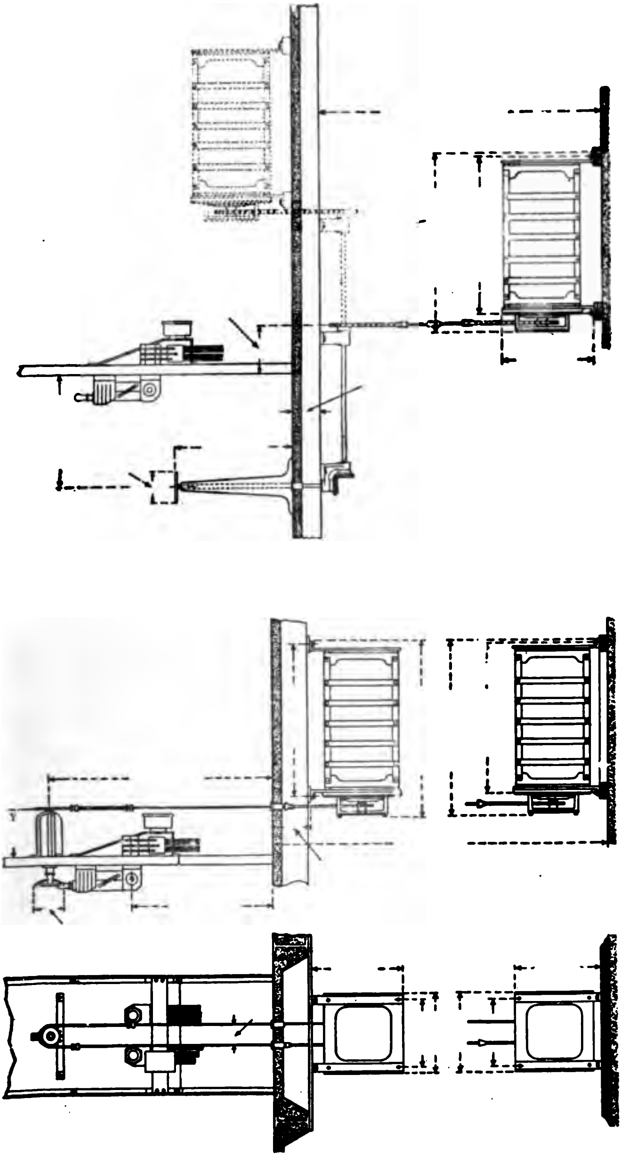


FIG. 58. COMMONLY-EMPLOYED ARRANGEMENTS FOR REMOTE MANUAL RHEOSTAT CONTROL

the form of cast-iron grids joined and supported by insulated rods and encased in a framework made up of angle irons and covered by screening. As in the other types, various steps of this resistance are connected to a set of contacts on a marble or slate face plate, which also carries the movable contact arm. In the larger sizes the plate carrying the contacts and contact lever is mounted on pipe or structural supports the same as any switchboard panel.

Direct-current machines are usually provided with field rheostats having a total resistance about equal to that of the winding of the field to be regulated, thus giving a variation of field strength from maximum to ½ maximum with a constant exciting voltage. The resistance of an alternating-current generator field rheostat is usually about twice that of the field winding, giving a variation in field current flow from maximum to ⅓ maximum, at constant voltage.

Control of Rheostats

Size of the rheostat, location of the switchboard and the mass of other equipment frequently mounted on the rear of the panels may require placing the rheostat in some remote location. This may necessitate remote electrical control, although if within close proximity to the switchboard a sprocket-and-chain arrangement with the hand wheel mounted on the face of a panel may be employed; if conditions require, the rheostat may be controlled by an hand wheel mounted on a pedestal and a series of shafts and gears in addition to the chains and sprockets. Various methods of remote manual control are illustrated in Fig. 58.

Electrically-operated rheostats are of the motor or solenoid type. The former, especially adapted for use in connection with field circuits carrying 300 amp. and more, is shown in Fig. 59. Attached to the contact arm is a gear which meshes with a worm near the end of the extended motor shaft. This motor is series wound and reversible, enabling the contact arm to be operated in either direction by means of a single-pole, double-throw switch mounted on the control panel of the main

switchboard. Limit switches operated by the contact arm automatically open the current-supply circuit to prevent over-travel.

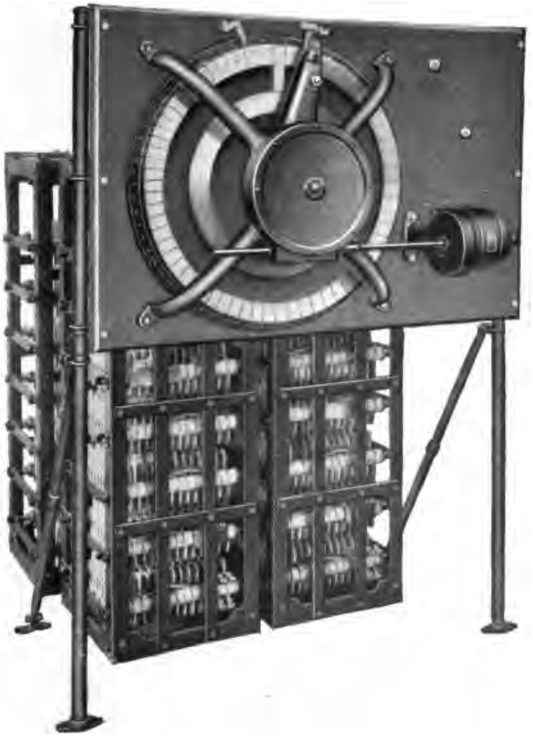


FIG. 59. CAST-GRID RHEOSTAT OPERATED BY ELECTRIC MOTOR

Figure 60 illustrates the diagram of connections of a General Electric solenoid-operated, ratchet-driven field rheostat, designed to carry currents of from 25 to 300 amp. and voltages up to and including 600 v.

Rigidly attached to the contact arm is a wheel, Fig. 61, provided with a knurled rim engaged by pawls which in turn are controlled by a core actuated in common by solenoids AA, Fig. 60. With no current flowing through either solenoid winding, the pawls are disengaged and

in their normal condition rest midway between the solenoids.

To cut resistance out of the field circuit, right-hand solenoid A is energized and engages the right-hand pawl, which, through the medium of the ratchet wheel,

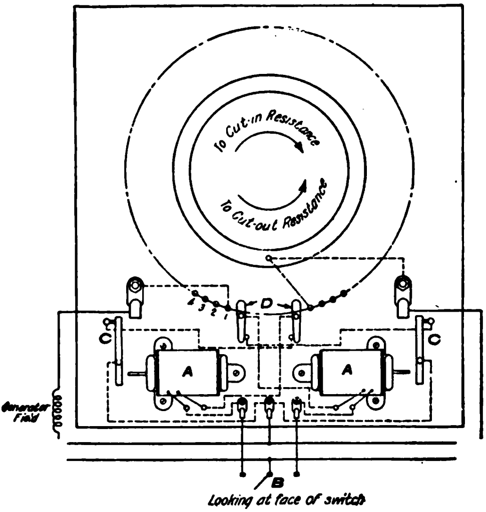


FIG. 60. DIAGRAM OF CONNECTIONS, GENERAL ELECTRIC SOLENOID-OPERATED, RATCHET-DRIVEN RHEOSTAT

FIG. 61. SOLENOID-OPERATED RATCHET-DRIVEN RHEOSTAT

moves the contact arm in a counter clockwise direction until the solenoid core has reached its extreme point of travel. The solenoid winding is then automatically opened by means of small switch C and the pawl immediately drawn to its neutral position by a spring, automatically closing the circuit of the solenoid switch by small switch C. This cycle is repeated as long as switch B is kept closed to the right.

To cut resistance into the field circuit, switch B is thrown to the left when the same action takes place

FIG. 62. FOUR-. TWO- AND SINGLE-UNIT PLATE RHEOSTATS FOR DIRECT MANUAL CONTROL

by left-hand solenoid A and switch C resulting in the contact arm moving in a clockwise direction.

Similar to the scheme employed in connection with the motor-operated field rheostat, each end of the switch dial is provided with a limit switch, D, automatically operated by the contact arm, thereby opening the solenoid circuit when the resistance is entirely cut in or out. This protects the apparatus in case the controlling circuit is left closed after the contact arm has reached its extreme point of travel in either direction.

Advantages of this type of switch as compared with those operated by motor are: Lower cost; closer regulation; less space required; lighter construction; compactness; parts more readily duplicated, and less attention required.

Selection, Installation and Care

Three essential points to be considered in selecting a rheostat are its durability of construction under the

service demanded of it; low heating limits to prolong the life of the insulation and reduce the fire hazard to a minimum; and ability to handle the necessary range of variation in the field resistance. Another important factor is a sufficient number of contacts or divisions of resistance to give proper regulation of voltage. Each additional step of resistance inserted should change the current capacity of the rheostat an equal amount and any such change in amperes per step is equal to the quotient obtained by dividing (the difference between the current flow with the rheostat short-circuited and the current flow when all resistance is in circuit), by the total number of steps or contacts. The current flow when *n* steps or contacts are in circuit is equal to the current flow when the rheostat is short-circuited minus the product of *n* times the change in amperes per step.

The radiating surface on each side of any plate-type field rheostat expressed in square inches, should be about 1/5 the product of (the current flow with rheostat short-circuited, times current flow with all resistance in circuit, times the total resistance of the rheostat). The current flow values are, of course, expressed in amperes while the resistance is in ohms, the value of which may readily be obtained from the name plate of the rheostat.

Due to the very nature of their function, rheostats are a source of heating and should, therefore, be installed well removed from all causes tending to interfere with an ample circulation of air through the elements. When necessary to place the rheostat near a wooden wall or any inflammable structure or material, some form of barrier such as a piece of ¼-in. asbestos board should be interposed, as a preventive measure.

As in the case of all other electrical machinery, cleanliness is of vital importance. When the resistance elements are of the wire- or ribbon-coil or cast-grid type, these should be blown out at frequent intervals and in order to eliminate flashovers and arcing, all contacts should be kept clean and bright and any accumulations of dirt between the contacts removed. Keeping the bearings well lubricated with a high-grade machine oil

will prevent deterioration and interference with the free action of the moving parts.

AUTOMATIC REGULATION

FIGURE 63 shows a diagram of the necessary connections for a voltage regulator for use with direct-current generators. This regulator consists of a main control magnet having a potential winding and a compensating

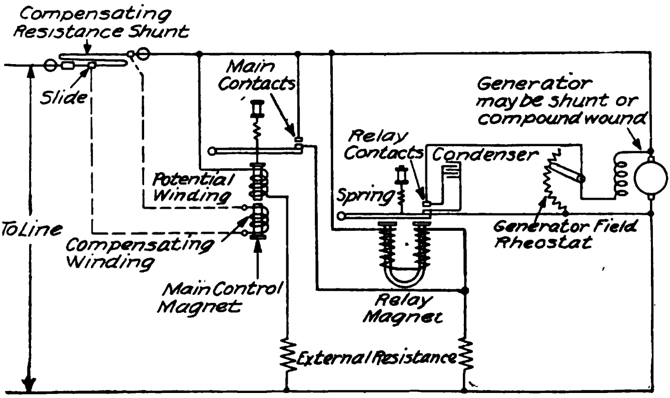


FIG. 63. ELEMENTARY DIAGRAM OF CONNECTIONS FOR TIRRILL DIRECT-CURRENT REGULATORS

winding, and a differentially wound relay. The compensating winding is generally connected to an adjustable compensating shunt placed in series with the main feeder, while the potential winding is connected directly across the feeders, as is also one section of the relay winding; the other section of the relay winding is connected to the busbars through the contacts of the main control magnet.

With a drop of generator voltage the main control magnet is weakened and due to the tension of the spring above, the pivoted lever is drawn upward and the main contacts closed. The lower section of the relay magnet is thus energized, neutralizing the action of the upper section, and due to the action of the relay spring the relay armature is lifted, the contacts closed and the generator field rheostat short-circuited. This, of course,

causes a rise of voltage which, acting upon the windings of the main control magnet, draws its core downward, the main contacts apart and opens the circuit of the lower section of the relay magnet winding; the relay contacts now open, the generator field rheostat is again cut into circuit, and as a consequence the voltage drops. The cycle is then repeated, and due to the high rate of vibration maintained, the terminal voltage of the machine may be kept at any desired value depending upon the adjustment employed.

A condenser is connected across the relay contacts to prevent destructive arcing.

Questions on Chapter VIII

1. What is the effect on the life of an incandescent lamp of voltage higher than normal? What is the effect on candlepower?
2. On what factors does the voltage generated by a d.c. dynamo depend?
3. Which of these factors is fixed after the machine is built? Which ones may be varied?
4. On what does the density of magnetic flux depend? How may it be controlled?
5. What different kinds of resistance are used in field rheostats?
6. How is connection made to these resistances?
7. What is the relation of rheostat resistance to resistance of the field winding for direct-current dynamos? For a.c. dynamos?
8. What two methods of electrical remote control of rheostats are in use?
9. How does the solenoid operated type work? What are its advantages?
10. What determines the size of step to be made in changing rheostat resistance?
11. What radiating surface should be provided?
12. How does the Tirrill regulator act on the rheostat to control voltage?
13. What is the use of the main control magnet? Of the relay magnet?
14. Why is a condenser used across the relay contacts?

CHAPTER IX

THREE-WIRE DIRECT-CURRENT SYSTEMS

2-Wire Generators and Motor-Generator Balancer Sets; 3-Wire Generators with Stationary and Revolving Balancer Coils

THREE-WIRE direct current systems find their greatest field of adaptability in moderate size isolated light and power plants. These systems allow the use of direct-current generating machinery and motors, possess the advantage of having available for use two different voltages and require less copper in the distribution line than a 2-wire system of equal capacity.

Modern systems of this type employ voltages of 220 between the two outside wires and 110 between either outside and the middle or neutral line, and may be fed either by the use of a standard 220-v., 2-wire generator operating in conjuction with a motor-generator balancer, or by the employment of a 3-wire generator.

As the generator of the first method is not unlike any other 2-wire direct-current generator, no description will be necessary other than a brief discussion of the use of the balancer.

With any unbalancing, such as is bound to exist to a greater or less extent in all 3-wire systems, the more heavily loaded side will suffer a decrease in voltage not experienced by the opposite side carrying the lighter load.

To remedy this trouble, a motor-generator balancer set is used. This consists of two small direct-current machines of identical ratings, directly connected and mounted on a common base. These machines are then electrically connected in series with each other and the set connected across the two outside lines with the neutral wire, as shown in Fig. 64, attached to their common point of connection.

With a balanced load, the two machines operate as motors. As an unbalanced condition is created, how-

ever, a greater drop of voltage occurs on the more heavily loaded side, so that the armature of the machine connected to that side is acted upon by a lesser voltage, while the machine on the lighter loaded side continues to operate under the higher voltage, as a motor driving the other machine as a generator, which then, for the

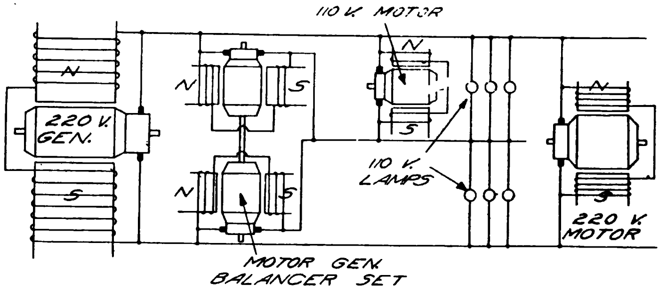


FIG. 64. 220-V. DIRECT-CURRENT GENERATOR AND MOTOR GENERATOR BALANCER SET

time being, supplies current for the excess load, thus balancing the system. By this action, it is seen that, by means of the balancer, the excess load on one side is practically thrown onto and carried by the side apparently having the lighter load.

As a rule, balancer sets have a combined capacity equal to from 4 to 10 per cent of the capacity of the generator with which they operate, and, as a method of protection against any excess of unbalancing which may occur, relays are provided, which, when the current through the neutral line exceeds some predetermined value, cause the main circuit breaker to be opened, thereby saving the machines from a possible burn-out.

Three-Wire Generators

Like the 2-wire machines, these generators are provided with balancers; but instead of employing a motor-generator set, stationary coils are used, either entirely separate from the machine but connected electrically thereto, or, as in some makes, mounted directly on the revolving armature. When these balancers are not integral with the machine, it is necessary to have col-

lector rings and brushes whereby the current is led from the armature winding to the balance coils, which are usually placed in some out-of-the-way location, such as behind the switchboard.

Theory of the 3-Wire Generator

Figure 65 is an elementary diagram showing the balance coil connections with the coils mounted on the armature.

A and B represent the direct-current brushes of the generator. The balance coil is symmetrically connected to the armature winding at the points C and D, with the neutral wire connected at mid-point E.

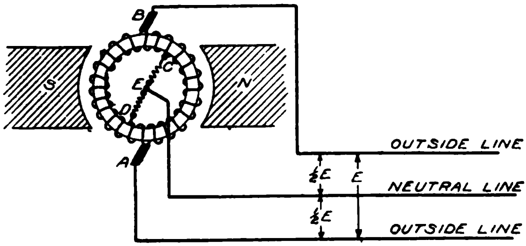


FIG. 65. DIAGRAM OF CONNECTIONS OF 3-WIRE GENERATOR WITH BALANCE COILS

Since connections of C and D will always be symmetrical with respect to brushes A and B, it is evident that the point E will at all times be a neutral point as between A and B, and may properly be used for the neutral connecting point. The same general argument and conclusion will apply for a multipolar machine, connections being made symmetrically to as many points of the winding as there are poles, so that current from the neutral wire of the system will divide among the various sets of brushes.

With the connection as shown in Fig. 65, but one collector ring is necessary, while if the balance coils are independent of the machine, taps C and D connect directly as shown in Fig. 66, which illustrates the connections of a typical Dobrowolsky 3-wire generator, to two collector rings. Since, however, with this connection a

tendency to pulsate is created, two additional taps are taken off at points F and G midway between C and D, resulting in the use of four collector rings. The arrangement of this connection, together with that of the accompanying balance coils, is shown in Fig. 67, and represents

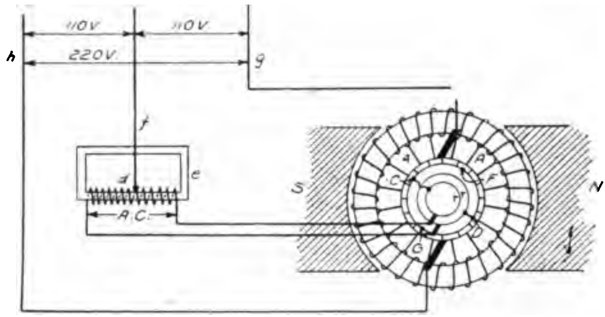


FIG. 66. CONNECTIONS FOR 3-WIRE GENERATOR WITH BALANCE COILS OUTSIDE

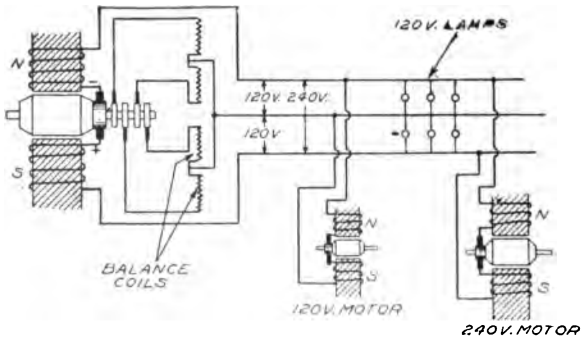


FIG. 67. 3-WIRE GENERATOR CONNECTIONS WITH FOUR SLIP RINGS AND SPLIT BALANCE COILS

the scheme employed by the manufacturers of 3-wire generators using separate balance coils connected across each pair of collector rings. As shown in this illustration, the middle points of the balancing coils are interconnected, and from this connection the neutral lead of the system is brought out.

Revolving Balancer

Some manufacturers of electrical machinery build 3-wire generators having revolving balance coils, which, as shown in Fig. 68, are placed on a circular magnetic core and mounted on a cast bracket bolted directly to the back end of the armature spider, and fitting under the

FIG. 68. ARMATURE OF 3-WIRE GENERATOR SHOWING REVOLVING BALANCER COILS

overhanging end windings, projecting but a short distance beyond them.

The various coils comprising this balancer are connected to the main armature winding at proper points, with the neutral connection taken through the armature spider to a single collector ring mounted in the outer end of the commutator shell.

Stationary Versus Revolving Balancers

Revolving balancers require the use of from one to four collector rings, brushes and brush holder rigging, and, in addition, require that the winding be extra heavily insulated to withstand the strain produced by centrifugal force. With the use of this integral balancer, however, necessity for the extra space occupied by the

stationary coils is avoided, and the required connecting cables are eliminated.

When separate balancer sets or coils are used, any direct-current generator capable of producing an electromotive force equal to that required across the two outside lines may be used, thus avoiding the purchase of an especially designed and built machine with its consequent higher cost.

Balancer Regulators

Equipment necessary to maintain a balanced voltage on a 3-wire direct-current system employing a balancer

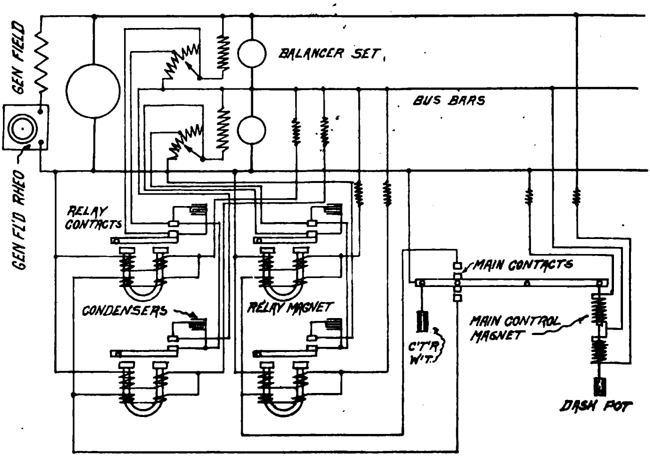


FIG. 69. REGULATOR CONNECTIONS FOR MAINTAINING BALANCED VOLTAGE ON BOTH SIDES OF 3-WIRE SYSTEM EMPLOYING BALANCER SET

set consists of four relay magnets and a main control magnet arranged and connected in the manner illustrated in Fig. 69. The relays are normally held open by the upper windings acting against springs.

Referring to the diagram, we note that the winding of the main control magnet consists of two opposed sections connected in series with resistances, across the two outside lines and their common connection tied to the neutral so that with balanced load both main contacts

are held open. Should, therefore, the voltage across the upper line and neutral become greater than that between the lower line and the neutral, the lower section

FIG. 70. GENERAL ELECTRIC TIRRILL VOLTAGE REGULATOR MOUNTED ON PEDESTAL

of the main control magnet would overpower the upper section and pull downward on its core and, as a result, the upper regular contacts will close, thus leaving open

the contacts of the relays on the left but closing those of the relays to the right. This inserts all resistance in the field of the upper balancer and short-circuits that in the field of the lower balancer, causing the former to act as a motor and the latter as a generator to raise the voltage across the lower busbars until it reaches and exceeds that across the upper busbars. The upper section of the main control magnet winding will now exert the greater pull, and as its plunger is drawn upward, the lower main contacts are closed and the contacts of the relays at the right opened and those of the relays at the left closed. We now find that the resistance of the field of the upper machine is short-circuited and that of the lower machine cut into circuit with the result that, due to the action explained above, the voltage across the upper bars will be raised. This cycle of operation is then repeated at a high rate of vibration, thus maintaining a balanced voltage on the system.

Questions on Chapter IX

1. Why is the three-wire system used?
2. What E. M. Fs. are usually employed?
3. What is the use of the balancer set?
4. Of what does the balancer consist, and how is it connected?
5. What capacity should the armatures of the balancer set have?
6. What is the use of the balancer coils in three-wire generators?
7. What two styles of balancer coils are used?
8. What are the advantages of the stationary balancer system?
9. How does the balancer regulator control voltages on the three-wire system?

CHAPTER X

ELEMENTS OF ALTERNATING CURRENTS

INDUCTANCE, CAPACITY AND POWER FACTOR

REFERRING to the underlying principles of the elementary electric generator with its bi-polar field and single-coil armature, Chapter I, we find that the electromotive force generated reverses in direction twice during each revolution of the coil, and that if instead of equipping such a machine with a commutator,

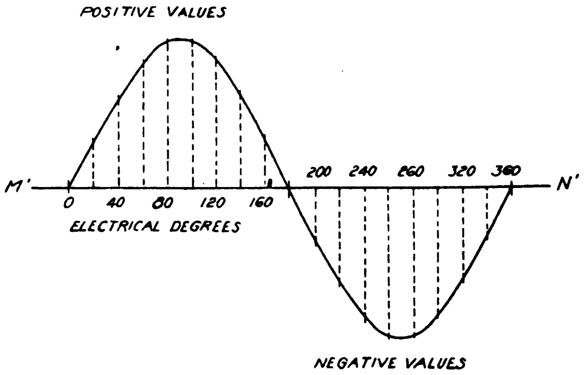


FIG. 71. INDICATING THE RISE AND FALL AND REVERSAL OF DIRECTION OF ELECTROMOTIVE FORCE INDUCED WITHIN THE WINDINGS OF A SINGLE-COIL ARMATURE REVOLVING BETWEEN THE POLE PIECES OF A BIPOLAR GENERATOR

the armature coil be connected to collector rings, the rise and fall and reversal of direction of electromotive force in the circuit supplied will be similar to that in the coil. A graphic representation of this is illustrated in Fig. 71. For sake of convenience, the values above the horizontal axis may be designated positive, and those below this axis, negative; a complete set of such values is

termed a cycle. The time duration of a cycle is termed a period and the number of cycles occurring a second is called frequency. In a simple alternating-current generator, having but one north and one south pole, and a single-coil armature, a complete cycle is passed through each time the armature makes one revolution, so that if

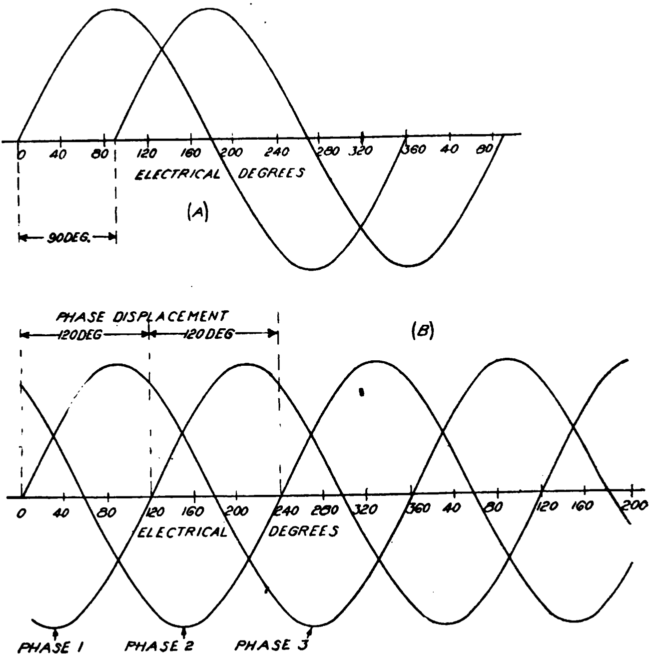


FIG. 72. TYPICAL (A) TWO-PHASE AND (B) THREE-PHASE ELECTROMOTIVE FORCE CURVES

the number of poles of any such machine is represented by P and the number of revolutions per second by n, the number of cycles per second or frequency f is equal to the product of P times n, divided by 2, or $f = P n \div 2$.

When the armature coils of an alternating-current generator are connected in series and the circuit thus formed terminates in two collector rings mounted upon the shaft, but insulated from it and from one another, the winding is said to be single-phase and the machine

is called a single-phase generator. In order, however, to meet the requirements of the polyphase induction motor and the rotary converter, it is necessary to equip alternating-current generator armatures with windings, such as will deliver polyphase (that is, more than one-phase) currents. This may be either two-phase or three-phase. In a two-phase machine, there are two sets of coils, the first set cutting the magnetic field at a maximum rate, when the induced electromotive force in the second set is zero; these electromotive forces are separated in phase by a quarter period or 90 deg., as shown at A, Fig. 72. At B of this same figure are shown the electromotive forces when the phase difference is 120 deg.

Maximum Average and Effective Values

The ideal alternating electromotive force and current curve is the so-called sine curve, which may be

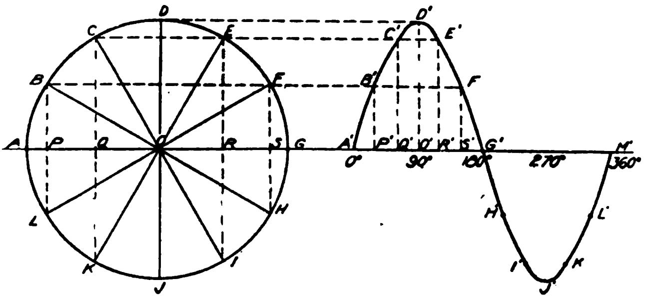


FIG. 73. SHOWING METHOD OF CONSTRUCTING THE SINE CURVE

readily constructed as indicated in Fig. 73. Upon the horizontal base line is drawn a circle having a radius O A and divided by means of radii O A, O B, etc., to O L, the spacing employed in this particular instance being 30 deg. Perpendiculars to the horizontal base line are dropped from the intersections of these various radii with the circumference of the circle as P B, Q C, O D and so forth. If now along the horizontal base line, as at the right of the figure, a given length of this line be laid off and divided into twelve equal parts, each to rep-

resent 30 deg. and perpendiculars erected corresponding in length to those at the left, that is B'P' equal to B P, C'Q' equal to C Q, etc., and the various points thus established as A'B' and so on to L' and M' connected, the curve will be a sine curve. That part from 0 to 180 deg. and above the horizontal line is of positive value, while that below the horizontal lines and extending from 180 to 360 deg. is of negative value.

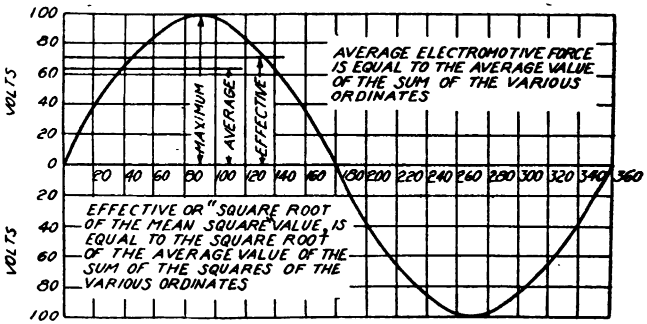


FIG. 74. INDICATING MAXIMUM, AVERAGE AND EFFECTIVE VALUES OF ELECTROMOTIVE FORCE

In the sine curve shown in Fig. 74, the electromotive force rises from zero in a positive direction to 100 v., then again to zero after which it reverses its direction and again reaches a value of 100 v., but of negative value, followed by a return to zero. It will be noted that the highest point reached, or, in other words, the maximum electromotive force has a value of 100 v. That is, the maximum value is 100 v. and while this is given but little attention in ordinary practice, account must be taken of it for the purpose of deducing formulas and the proportioning of insulation.

Measuring the lengths of the ordinates erected at the various points along the horizontal base line, that is, in this particular case, at every 20 deg., and dividing the sum of these lengths by the number of points selected, we obtain the average length of the ordinates, which is in reality the average value of the electromotive force. By actual measurement of the ordinates of a sine

curve, we obtain an average value of 0.637 of the maximum or in this particular instance, the average electromotive force would have a value of 0.637 times 100, or 63.7 v.

Electrical instruments do not, however, indicate the maximum value nor the average value, but the effective value of the electromotive force and current and it is therefore this which is dealt with the most. The effective value is in electrical engineering parlance frequently referred to as "the square root of the mean square" value and is obtained from a true sine curve by taking the square root of the mean value of the sum of the squares of the various ordinates. Its value is 0.707 of that of the maximum value, so that as in Fig. 74, where the maximum value is 100 v., the effective value is equal to 0.707 times 100, or 70.7 v.

INDUCTANCE

STRICTLY SPEAKING, there are two kinds of inductance, namely, mutual inductance and self inductance. As already explained in Chapter II, a conductor carrying an electric current is surrounded by concentric lines of magnetic force which decrease in intensity with increase of distance from the center of the conductor. If a second "dead" conductor is within close proximity to a conductor carrying current, that is, sufficiently close to be within the magnetic field of the first conductor, steady flow of electric current through the first conductor will have no effect upon the "dead" one. If, however, the strength of the current through the first conductor varies periodically, non-periodically, uniformly, or non-uniformly, the strength of the magnetic field will vary likewise and as a consequence due to such variation of magnetic field there will be induced within the second conductor an electromotive force, the values and polarity of which are dependent upon the variation of the change of current strength within the first conductor and consequently upon the variation of strength of magnetic field surrounding this first conductor. If the current flow through the first conductor varies as a sine curve, the induced electromotive force values will also

follow the path of a sine curve although the direction of the induced electromotive force at any instant is opposite to the direction of the electromotive force maintaining the flow of current through the first conductor.

This phenomenon is termed mutal inductance.

On the other hand, let us assume having a coil of wire wound upon an iron core and carrying a current of electricity. Magnetic lines of force as previously explained will surround this so-called solenoid. Let us

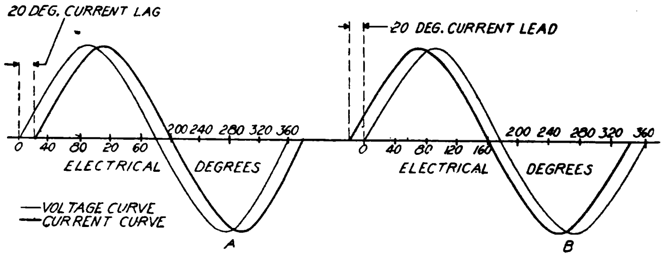


FIG. 75. ILLUSTRATING (A) LAGGING (B) LEADING CURRENTS

further assume, however, that the flow of current through this coil is suddenly reduced. As a result, the magnetic lines of force will break down, that is, the body of the flux will contract, and as the various turns of wire making up the coil lie in the path of these receding lines of force, an electromotive force termed the counter-electromotive force, is induced within the conductors. This electromotive force, which also is opposite in direction to that of the inducing electromotive force, is what is continuously being created within the windings of a coil of wire supplied with alternating current.

Self inductance is the name applied to this phenomenon, the counter-electromotive force of which is proportional to the rate of change of current provided the permeability of the medium around the conductor remains unchanged. The unit of inductance is the henry represented by the letter L and is that inductance existing when a uniform variation of current at the rate of 1 amp. per second produces a counter-electromotive force of 1 v.

With only resistance included in a circuit supplied with alternating current, the current although of different unit value rises, falls and alternates in unison with the electromotive force and as a consequence the graphic representation of such conditions would be as indicated in Fig. 71. In other words, the current and electromotitve force are in "phase" or in "step." If, however, inductance is encountered, the current will lag behind the electromotive force in the manner indicated at A in Fig. 75; that is, as in this particular example, the electromotive force will have reached some appreciable value before the current starts from zero and likewise the maximum value of the current will not have been reached until after the voltage wave reaches its crest. This same difference in angularity, in this particular instance 20 deg., maintains as long the value of the inductance remains unchanged; but, as the value of the inductance increases, the angular difference between the electromotive force and current waves increases until the angular difference may be nearly 90 deg. Actually, however, a difference of 90 deg. cannot be reached. With little inductance there will be a small degree of lag; with considerable inductance the lag will tend to approach 90 deg.

CAPACITY

ANOTHER PHENOMENON of alternating currents is capacity, also sometimes termed permittance. This, the effects of which, as will be evident, are opposite to those of inductance, is the power of storing or holding an electric charge.

To understand more readily the nature of this property of alternating currents, let us refer to Fig. 76 where at A is shown a plunger pump P each end of the cylinder of which is connected by piping to a chamber fitted with an elastic diaphragm D D, while at B is illustrated a single-phase generator G the brushes of which, through the medium of the necessary connecting wires, tie in with the conducting plates C C insulated one from the other by means of a dielectric or insulator D D.

Assuming that the cylinder of the pump, connecting pipes and the chamber containing the diaphragm are filled with water and that the piston of the pump is given reciprocating motion. Immediately the water is set in motion with the result that as the piston moves upward diaphragm B is distended downward, while with a reverse motion of the piston, that is downward, diaphragm D D is distended upward. It is then evident that the alternating pressure generated by the pump must not only overcome the resistance of the pipe be-

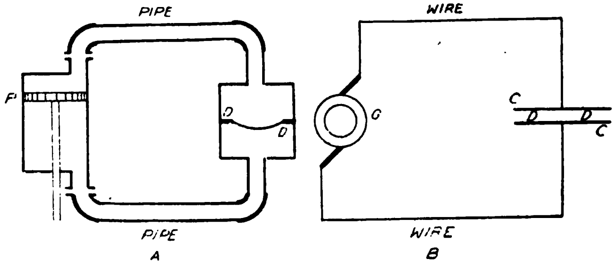


FIG. 76. ILLUSTRATING PHENOMENA OF CAPACITY

tween the pump and the chamber, but a considerable portion of such pressure must be employed in overcoming the inertia of the water in the pipe, first in establishing the current of water, and then stopping the current and starting it again in the opposite direction; and also to distend the diaphragm. In a like manner, the electromotive force generated by machine G must not only overcome the resistance of the connecting wires and the inductance of the circuit (which corresponds to the inertia referred to in the pump arrangement just cited), but it must also assist in producing an electrical stress which is created in the insulating material D D between plates C C as these are electrically charged first in one direction and then in the opposite direction. That is, due to the alternating values of the electromotive force, first the upper plate becomes positive and the lower negative, then the upper plate negative and the lower one positive. This arrangement of plates C C separated by the insulating medium of dielectric D D

constitutes a condenser which permits an alternating current to surge back and forth but prevents the flow of a steady current in the same manner as diaphragm of A permits the surging of the current of water but prevents continuous flow.

The unit of capacity is the farad and is the capacity which a condenser possesses when one coulomb* of charge is drawn out of one plate and forced into the other by an electromotive force of 1 v.

Where C is the electrostatic capacity of any condenser and E the electromotive force in volts, q, the charge drawn out of one condenser plate and forced into the other, is equal to the product of C and E.

With the introduction of capacity the effect is opposite to that due to the presence of inductance. Instead of lagging behind the electromotive force the current will tend, as indicated at B, Fig. 75, to lead the electromotive force.

E. M. F. and Current Waves

Electromotive force and current waves may readily be obtained by means of either one of two methods,

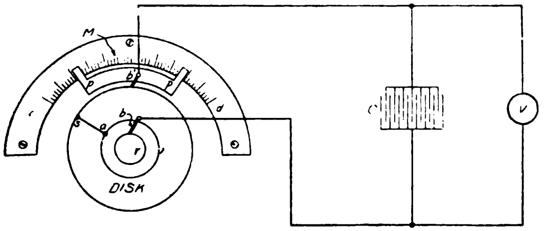


FIG. 77a. CONTACT MAKER

namely, by the use of what is known as the contact maker or by means of the oscillograph.

The contact maker, the essential features of which are shown in Fig 77a, is a device for repeatedly connecting a large condenser, C, to the terminal of an alternating-current generator at a certain instant of an elec-

* The coulomb is an ampere-second; that is, the equivalent of the flow of 1 amp. for a period of 1 sec.

tromotive force cycle, thus keeping the condenser charged up to the voltage e that exists at the given instant in the cycle, in order that the value of e may be measured by voltmeter V.

A disk of insulating material is fixed to the armature shaft of the alternator of which the electromotive force curve is to be determined, and a thin metal brush b^1 rubs on the edge of this disk and makes momentary contact once per revolution with a narrow metal strip S which is set in the edge of the disk. The brush b^1 is supported on a sector pp which slides around on the inner edge of the divided circle cd, and the reading on the divided circle of the mark M indicates the position of the brush b^1.

One terminal of the condenser is permanently connected to one collector ring r of the alternator by means of brush b, while the other terminal is connected to brush b^1 and thence through the strips and wire a to the other collector ring r^1.

It is essential that voltmeter V take but a small amount of current so that the condenser may supply the required current during the intervals between contacts of b^1 and S without perceptible decrease of voltage across its terminals.

A complete cycle of electromotive force values is obtained by shifting sector pp, step by step, over the angular distance between two adjacent north poles (or south poles) of the field magnet, noting the corresponding voltmeter readings and plotting a curve therefrom, using the circle readings as abscissas and the voltmeter readings as ordinates. To obtain a current curve, the current is made to flow through a non-inductive resistance R; the electromotive force curve across the non-inductive resistance is determined, and the values of the ordinates of this electromotive force curve are divided by the value of R to give the points on the current curve.

The Oscillograph

The oscillograph is a galvanometer constructed with an extremely light needle the period of vibration of which is extremely short.

In general this instrument consists of 2 fine wires, WW, Fig. 77b, stretched close together between the poles NS of a strong magnet. A light mirror M is attached to the 2 wires through which the current to be measured flows down one and up the other so that one wire is pushed backwards and the other forwards, thus deflecting the mirror while a beam of bright light falls thereon and is reflected to a moving photographic plate upon which is left a permanent trace of the movements of the mirror. Alternator A, of which the electromotive force curve is to be determined, is connected through

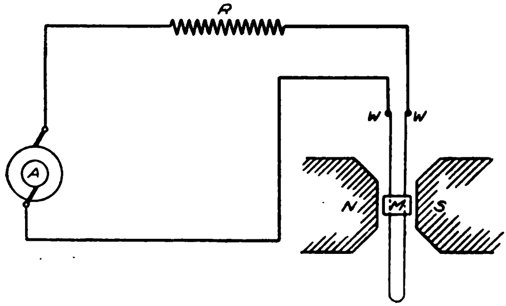


FIG. 77b. ELEMENTARY PRINCIPLE OF OSCILLOGRAPH

a non-inductive resistance R to the oscillograph as shown in Fig. 77b.

Power Factor

As in the case of direct-current work, the power delivered by a single-phase alternating-current generator to a circuit or consuming device in which only resistance exists (no inductance or capacity present), is at any instant equal to the product of the number of volts and the number of amperes of current flow, so that as indicated at A in Fig. 77c, the instantaneous values of power rise and fall in phase from zero to maximum and back to zero again for each half current and electromotive force cycle. In this particular instance, the current and electromotive force reach maximum values of 40 amp. and 100 v. respectively and as a consequence and as indicated by the power curve, the maximum number

of watts is equal to 40 times 100, or 4000. For all other instantantous current and electromotive force values, the corresponding number of watts may be obtained by multiplication of such values and while the electromotive force and the current alternate through positive and negative values, the product, due to the fact that the instantaneous values are of like sign (positive or nega-

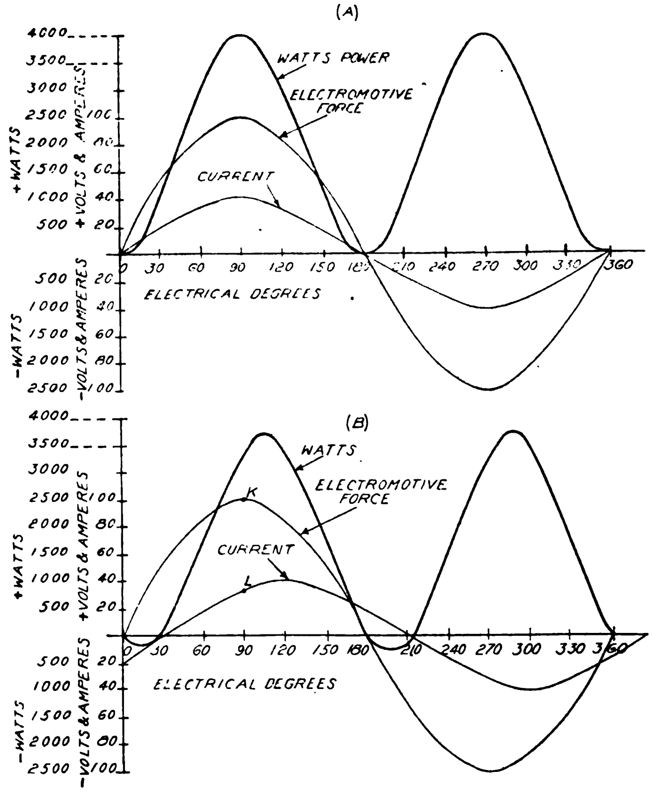


FIG. 77c. ILLUSTRATING EFFECT OF LAG OF CURRENT UPON POWER

tive), is always positive. It is for this reason that no points in the power curve fall below the zero line.

Where, however, due to inductance or capacity, the electromotive force and current are out of phase, as

where the current lags behind or leads the electromotive force, negative power values as shown at B, Fig. 77c, are introduced. As indicated in this set of curves, the current lags 30 deg. behind the electromotive force, so that from zero to 30 deg. positive electromotive force values are multiplied by negative current values with the result that, as indicated, the corresponding values of power are negative in character. Beyond 30 deg., however, and up to 180 deg. all current and electromotive force values are positive and the corresponding power values positive. Another negative power loop occurs between 180 and 215 deg. after which, on account of all current and electromotive force values being of like sign (negative), the power curve is positive.

It is obvious, therefore, that where inductance or capacity exist P is not equal to E I where P is the power in watts, E the electromotive force in volts and I the current in amperes. A factor known as the power factor and having a value depending upon the degree of lag or lead must be considered. Or, P is equal to E I cos. A, where cos. A is the cosine of the angle of lag or lead expressed as a decimal.

The values of the cosines of angles ranging from zero to 90 deg. are given in the table, Fig. 78. The cosine of 30 deg. is, we find from the table, equal to 0.866, so that if the electromotive force has a value of 100 v. and the current 33 amp. the power in watts is equal to

$$P = E\ I \cos. A, \text{ or,}$$
$$P = 100 \times 33 \times 0.866$$
$$P = 2857.8 \text{ w.} = 2.8578 \text{ kw.}$$

and not = E I, or 100 × 33, or 3300 w., or 3.3 kw. as would be the case where the power factor is 1 (that is, where no inductance or capacity are encountered).

Let us assume having a generator which according to instruments is as above delivering 33 amp. of current while the voltage is 100, and the indicating wattmeter reads 2857 w. The product of the volt and ammeter readings is generally referred to as the apparent watts and the reading of the indicating wattmeter is the real watts. Dividing the latter by the former, that is, the real wats or 2857 by the apparent watts or 3300, we obtain as

a quotient 0.866 the value of the power factor or, as it is more generally expressed, 86.6 per cent.

Result of Low Power Factor

An alternating-current generator may at any time appear, from its volt and ammeter readings, to be carrying full load, when, in reality, if a wattmeter be

Degrees	Cosine	Degrees	Cosine	Degrees	Cosine
1	0.99985	31	0.85717	61	0.48481
2	0.99939	32	0.84805	62	0.46947
3	0.99863	33	0.83867	63	0.45399
4	0.99756	34	0.82904	64	0.43837
5	0.99619	35	0.81915	65	0.42262
6	0.99452	36	0.80902	66	0.40674
7	0.99255	37	0.79863	67	0.39073
8	0.99027	38	0.78801	68	0.37461
9	0.98769	39	0.77715	69	0.35837
10	0.98481	40	0.76604	70	0.34202
11	0.98163	41	0.75471	71	0.32557
12	0.97815	42	0.74314	72	0.30902
13	0.97437	43	0.73135	73	0.29237
14	0.97029	44	0.71934	74	0.27564
15	0.96592	45	0.70711	75	0.25882
16	0.96126	46	0.69466	76	0.24192
17	0.95630	47	0.68200	77	0.22495
18	0.95106	48	0.66913	78	0.20791
19	0.94552	49	0.65606	79	0.19081
20	0.93969	50	0.64279	80	0.17365
21	0.93358	51	0.62932	81	0.15643
22	0.92718	52	0.61566	82	0.13917
23	0.92050	53	0.60181	83	0.12187
24	0.91354	54	0.58778	84	0.10453
25	0.90631	55	0.57358	85	0.08715
26	0.89879	56	0.55919	86	0.06976
27	0.89101	57	0.54464	87	0.05234
28	0.88295	58	0.52992	88	0.03490
29	0.87462	59	0.51504	89	0.01745
30	0.86603	60	0.50000	90	0.00000

FIG. 78. VALUES OF COSINE OF ANGLES FROM 0 TO 90 DEG.

used we may find that the machine is delivering in kilowatts but, let us say, 75 per cent of its rated capacity.

When the load on an alternator consists principally of transformers or induction motors, we find that the current lags behind the electromotive force in phase; while, if the load has a condenser effect, such as produced by an over-excited synchronous motor, the current will lead the electromotive force. In either case, upon a comparison of voltmeter, ammeter and wattmeter read-

ings we find that the apparent watts load, that obtained by multiplying the current flow in amperes by the electromotive force in volts, is greater than the actual watts load as indicated by the wattmeter. Let us assume a circuit carrying 130 amp. at a voltage of 110 and with the current lagging 20 deg.

From our meter readings we find that apparently 110 times 130, or 14,300 w. or 14.3 kw. are being delivered, but this is not the true number of watts or kilowatts. The true number of watts is found by multiplying the number of amperes by the volts and by a factor called the power factor whose value depends upon the size of the angle of lead or lag. While the value of the power factor may be obtained by the use of the cosine table, we may also find its value by dividing the wattmeter reading by the product of the volt and ammeter readings expressed in watts. In other words, the power factor is the ratio between the true watts and the apparent watts. It is also represented by the cosine of the angle of lead or lag when the electromotive force and current waves are not distorted.

To distinguish them, the apparent output, that is the product of the voltmeter and ammeter readings, is usually expressed as kilovolt amperes, abbreviated kv.a., while the true output is expressed as kilowatts or kw.

Referring to the case cited above, we find that the actual power being delivered is equal to the product of the volts times the amperes times the cosine of 20 deg. which is found to be 0.9396. We have, therefore, in this case, the true watts equal to $110 \times 130 \times 0.9396 = 13,$-436 w., or 13.436 kw.

Switchboards may be equipped with ammeters, voltmeters and power-factor meters, in which case the true watts may be obtained in the manner just shown, power factor meters indicating directly the per cent power factor, or, in other words, the cosine of the angle of lag or lead. Again, a board may not be supplied with a power factor meter but may have mounted upon it in addition to the regular voltmeters and ammeters, a wattmeter or meters Under such conditions the power factor may be determined by dividing the wattmeter

reading expressed in watts by the product of the volt and ammeter readings. The quotient will be the cosine of the angle of lead or lag or when multiplied by 100 will give the per cent power factor.

Modern switchboards, especially those controlling large outputs, are generally equipped with voltmeters, ammeters, wattmeters or kilowatt meters and power-factor meters, so that an accurate check on the accuracy of the various instruments may easily be obtained by comparing the volt-ammeter, power-factor meter and wattmeter readings.

Effect of Low Power Factor

A low power factor with current leading is as detrimental to the proper operation of a generating station of transmission system as is a low power factor with current lagging, although it is the latter which is generally met and which must be corrected.

With a system, the power factor of which is comparatively low, excessive generator, switchboard and transmission line capacity must be provided, entailing considerable additional expense. The size of generator windings required, the capacity of the ammeters and wattmeters and the size of the controlling switches, circuit breakers and transmission lines needed are directly proportional to the current flow which, in the case of a low power factor, becomes large as compared to the number of watts or kilowatts actually being delivered.

An example may illustrate the truth of this more effectively. Let us consider a station of 2000 kw. capacity, operating at a normal power factor of 65 per cent. We know that with unity power factor, for full-load operation, the capacity of the station is 2000 kw. and with a generated voltage of 2300, the windings of the machines, the size of the connecting cables, switches, ammeters, wattmeters, busbars and outgoing lines need be no greater than is necessary to carry 2,000,000 divided by 2300, or about 870 amp., and allowing for a small possible overload, let us say 900 amp.

With a power factor of but 65 per cent and the station still called upon for 2000 kw., we find somewhat

extraordinary requirements in the size of equipment. Under such conditions, the true watts are equal to 2,000,000, so that with the above-named power factor, the apparent watts must be 2,000,000 divided by 65 times 100, or 3,077,000 v.amp. or 3077 kv.a., and as the voltage remains constant an actual current flow of 3,077,000 divided by 2300, or 1338 amp. will exist. At normal rated capacity and unity power factor the generators and other equipment as outlined above have

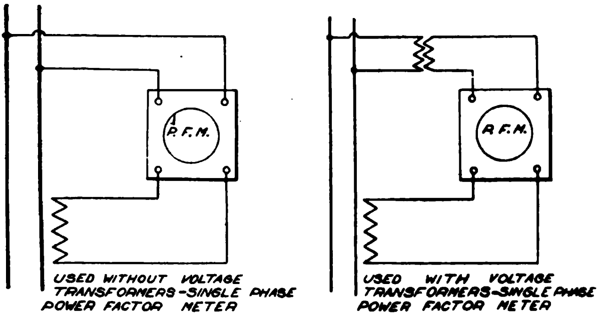


FIG. 79. DIAGRAM OF CONNECTIONS OF POWER FACTOR METER ON SINGLE PHASE CIRCUIT

been designed for but a trifle over 869 amp., so that when operating at 65 per cent power factor this equipment will be called upon to carry an additional 486 amp. or 53.8 per cent more current than its normal rated capacity.

To remedy this trouble, it is necessary that a system be designed and equipped to operate at as high a power factor as is possible. Even under the best of conditions, power plant operators find it extremely difficult to maintain a power factor of exactly unity, hence, designers of power plant equipment have compromised by building and using machinery and apparatus of such capacity as will readily care for the load with a power factor at or above a given specified value. Present day designers of generating and transmission equipment allow for a minimum of approximately 80 or 85 per cent power factor, with the expectation that anything below this value shall be corrected beyond the switchboard.

Frequently, operators who do not understand the important role that high power factor plays in the operation of a generating station and transmission system, are puzzled at the effects which a low power factor produces.

Switchboard wattmeters or kilowatt meters may be indicating a normal load, while at the same time the generating unit may be showing all indications of carrying an extremely heavy overload, as evidenced by a slowing down of the prime mover and heating of the generators and of transformers when these are interposed between the machines and the load. Likewise, all cables, switchboard instruments, busbars and transmission lines will be carrying a current greatly in excess of their rated capacity, resulting in a heating of all current carrying parts, and a considerable drop in voltage. This trouble may be of such magnitude as to cause the circuit breakers to open or, in the case of their failure, may even result in a burn out.

Measurement of Power Factor

Power-factor meters perform, automatically, an operation that otherwise requires the simultaneous reading of 3 or more separate meters and the computation of the power factor from their indications. These meters indicate upon a graduated scale the power factor of the circuit to which they are connected.

Power Factor Meters

Power factor meters, the diagrams of connections of which are shown in Fig. 79a, are designed to indicate directly and accurately the power factor of alternating-current circuits. These instruments operate upon the rotating field principle, the field being produced by the current of the metered circuit in coils set at an angle to each other. Under the influence of the field is provided a movable iron vane or armature, magnetized by a coil whose current is in phase with the voltage of one phase of the circuit. As the iron vane is attracted or repelled by the rotating field of the current coils, it will take up a position where the zero of the rotating field occurs at the same instant as the zero of its own field. Thus its

position will always indicate the phase angle between the voltage and the current of the circuit. The pointer attached to the armature, therefore, indicates this angle, and by marking on the scale the cosine of the angle the power factor is read directly.

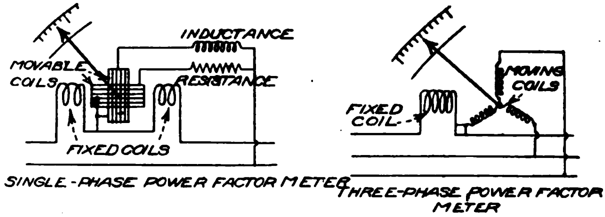


FIG. 79a. TYPICAL POWER FACTOR METER CONNECTIONS

In the three-phase meter the rotating field is produced by three coils spaced 120 deg. apart and connected in the three phases of the circuit; in the two-phase meter by two current coils spaced at 90 deg. In the single-phase meter the relative position of voltage and current coils is reversed and the rotating field is produced by means of a split-phase winding, Fig. 79. No connection to the moving element is necessary.

A type of meter extensively used on 3-phase circuits consists of a field-current coil, connected in series with the middle line within which two potential coils are mounted on a vertical shaft. These coils are connected between the middle and outside lines. The resultant effort tending to deflect the shaft will vary with the power factor, because the phase relation of the currents in the movable coils to the current in the fixed coil will change with the power factor and the instrument can be calibrated so that the pointer attached to the movable coils will indicate the power factor.

Figure 80 illustrates the diagram of connections of another type of power factor meter for use on 2-phase circuits. The current in the series coils produces a rotating field while the current in the shunt coil produces an oscillating field. The shunt or electromotive force coil is free to rotate and will take up a position in

which its oscillating field will be in time phase with the resultant rotating field in that plane. If the electromotive force is in phase with the current, the coil will take the position showing 100 per cent.

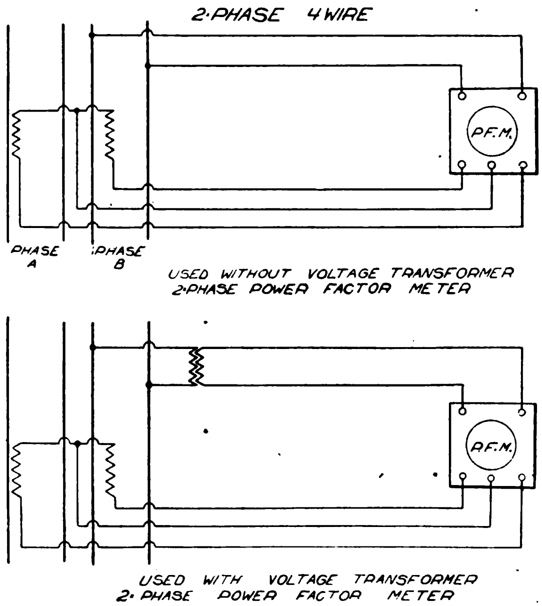


FIG. 80. DIAGRAM OF CONNECTIONS OF POWER FACTOR METER ON 2-PHASE CIRCUIT

A method employed to some extent in the determination of the power factor of a 3-phase circuit is by the 2-wattmeter method. With the meters connected in the regular manner, the power factor of the circuit may be determined by applying the ratio of their readings to the chart shown in Fig. 82. If this ratio should, for example, be 0.9, we find from the chart that the power factor is about 100 per cent; if the ratio is 0.4, the power factor is 80 per cent. If, however, one meter only indicates, the ratio of readings will consequently be 0, indicating a power factor of 50 per cent. Should, however, this ratio be —0.4, due to a negative reading of one of the instruments, the power factor, instead of being 80 per cent as before, is approximately 24 per cent.

Let us assume the readings of 2 wattmeters connected to a 3-phase circuit to be 2000 and 6000 respectively, so that the ratio is 0.333. We would then find that, due to both readings being of like sign, causing 0.333 to be positive, the power factor is about 74 per cent.

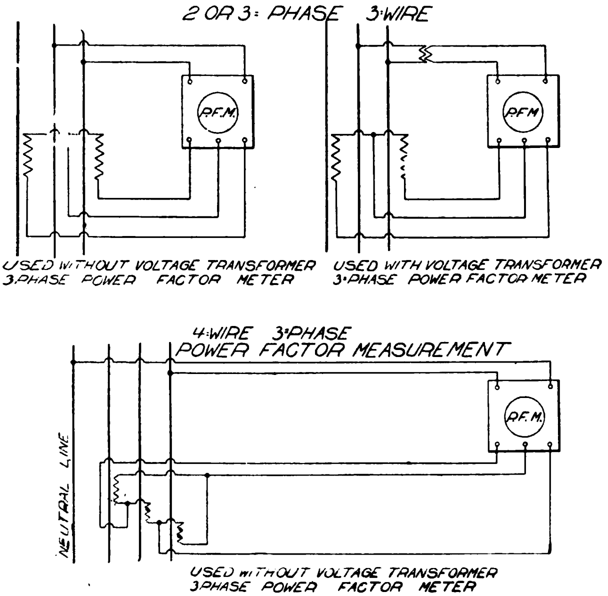


FIG. 81. DIAGRAM OF CONNECTIONS OF POWER FACTOR METER ON 3-PHASE CIRCUIT

Again, let us say that the readings be —2500 and +5000 watts. The ratio between the 2 values will be —0.5, so that by referring to the chart, we find a power factor of 20 per cent.

Reactive Factor Meters

Another type of instrument now used extensively is the reactive factor meter, which instead of indicating the cosine of the angle of lag or lead as does the power factor meter, indicates the sine of the angle of lag or lead. This, in every case, is greater than the difference between unity and power factor, and therefore shows

most emphatically the idle component of the volt-amperes, thus inducing operators to correct more quickly the waste due to a poor power factor, and makes the use of these meters particularly desirable in the operation of rotary converters, where a slight drop in power factor will result in considerable armature heating.

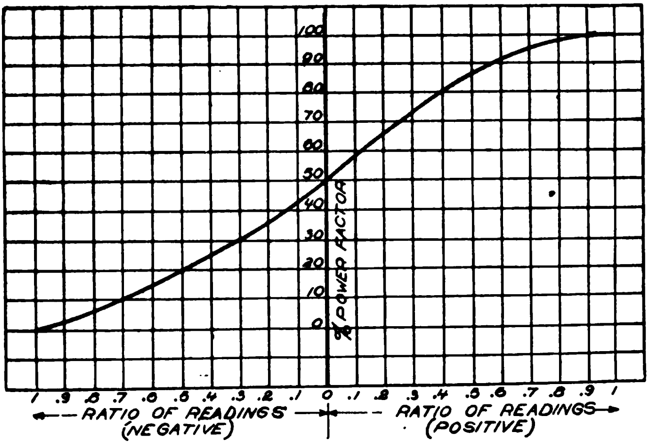


FIG. 82. RELATION OF RATIO OF WATTMETER READINGS TO POWER FACTOR, 3-PHASE CIRCUIT

With an angle of 10 deg., either lead or lag, the power factor will be 98.5 per cent, because the cosine of 10 deg. is 0.985, and the reactive factor will be 17.3 per cent, the sine of 10 deg. being 0.173. Likewise, with a power factor of 95 per cent, the reactive factor is 31.5 per cent.

Power factor and reactive factor are equal at only 70.7 per cent. At higher power factors, the load conditions are more conspicuously indicated on reactive factor scale, while at lower power factor the reverse is true, and as a consequence, reactive factor indicators find their greater usefulness on circuits the power factors of which vary from 70 to 100 per cent.

Typical power factor values for various types of apparatus as given by F. D. Newbury are shown in the table, Fig. 83.

Alternator Ratings

As in the case of direct-current generators, the output of an alternator in amperes is dependent upon the

Apparatus	Per Cent Power Factor	Remarks
Incandescent Lighting	90 to 95	With small lowering transformers.
A. C. Inclosed Arc Lamps	60 to 75	With constant current transformers.
D. C. Metallic Arc Lamps	55 to 70	With rectifiers.
Single-Phase Induction Motor Squirrel Cage Rotor		
¼ to 1 hp.	55 to 75	At rated load
1 to 10 "	75 to 86	" " "
Polyphase Induction Motor Squirrel Cage Rotor		
1 to 10 hp.	75 to 91	At rated load
10 to 50 "	85 to 92	" " "
Polyphase Induction Motor Phase Wound Rotor		
5 to 20 hp.	80 to 89	At rated load
20 to 100 "	82 to 90	
Induction Motors (General)	60 to 85	Depending whether motors are carrying full load.
Arc Furnaces	80 to 90	
Induction Furnaces	60 to 70	
Welding Transformers	50 to 70	
Synchronous Motors		Adjustment between practically zero power factor leading to zero power factor lagging.
Rotary Converters, Compound Wound		Power factor at full load can be adjusted to practically 100 per cent. At light loads it will be lagging; and at overloads slightly leading.
Rotary Converters, Shunt Wound		Power factor can be adjusted to any desired value and will be fairly constant at all loads with the same field rheostat adjustment. Should not be operated below 95 per cent power factor leading or lagging at full load or overload.

FIG. 83. APPROXIMATE VALUES OF POWER FACTOR OF VARIOUS TYPES OF APPARATUS

degree of heat generated within the machine; or, in other words, the heating effect determines the current rating of the machine, and the power rating of an alternating-current generator is always understood to be the power it can deliver at unity power factor without undue rise

in temperature; that is, the power rating is the product of its rated voltage and its rated current.

Unlike the direct-current generator, however, except under conditions of unity power factor, the power rating of an alternator should not be expressed in watts, or in kilowatts, but in volt-amperes or kilovolt-amperes. The reason for this is obvious when we consider the case of a typical machine operating at various power factors. Let us assume a 2300-v. alternating-current generator having a current rating of 500 amp. At full load and at a power factor of unity, the power rating is equal to the product of 2300 and 500, or 1,150,000 volt-amperes or 1150 kv.a. which, under the power factor conditions given, may be expressed as 1150 kw. If, however, this machine is made to deliver a like amount of energy, namely 1150 kw., but at a power factor of 0.80, or 80 per cent, the current flow will be in excess of 500 amp.; to be exact, it would be equal to the quotient obtained by dividing 1,150,000 by the product of 2300 and 0.8, or 625 amp. and as a consequence, undue heating would result. It is to guard against such occurrences that alternating-current generators are rated in kilovolt-amperes rather than kilowatts.

Questions on Chapter X

1. Why does voltage reverse in direction in an armature conductor?
2. What is meant by a cycle? By frequency? By a period?
3. What is single phase? Polyphase?
4. How are two-phase and three-phase currents related in time?
5. In a two-phase generator (sine wave), what is the value of phase 1 current when phase 2 current is zero?
6. In a three-phase generator (sine wave), what is the value of phase 1 current when phase 2 current is zero? When phase 3 current is zero?
7. What value of e.m.f. and current are indicated by electrical instruments? What is their relation to maximum values?

8. How is inductance caused?
9. What kinds of apparatus will bring inductance into a circuit?
10. What is the effect of inductance on the relation of current to voltage?
11. What kind of circuit will act the same whether either direct or alternating current is carried?
12. What is the effect of capacity on the relation of current to voltage?
13. Can inductance and capacity effects be made to neutralize each other?
14. Will the power be greater or less in an inductive circuit than in a non-inductive, voltage and current curves being the same?
15. Why must a power factor be used in figuring the power in an a.c. circuit?
16. How can the power factor be found if voltmeter, ammeter and wattmeter are available?
17. What are the effective values of voltage and current (sine waves) when the maximum values are 220 volts and 75 amperes? (155.5 v.; 53 amp.)
18. What would be the power delivered in question 17 with an angle of lag of 20 deg.? (7750 watts.)
19. In an a.c. circuit the voltage is 2300, current 55.4 amp., and wattmeter reading 118,645. What is the power factor? (93 per cent.)
20. Why are a.c. generators rated in kilovolt amperes (kv.a.)?
21. What would be the danger if a 6600 volt machine, designed for 200 amperes was allowed to carry a load of 1320 kw. at 75 per cent power factor? How much current would it have to supply? (267 amp.)

CHAPTER XI

ALTERNATING-CURRENT LAWS

INDUCTIVE AND CAPACITY REACTANCE; RESONANCE

WHEN a conductor carries an alternating current the current density near the surface is considerably greater than that near the axis, and, as a consequence, the virtual resistance of the conductor is somewhat in excess of its actual resistance. This phenomena is called "skin effect," and is present to a greater degree in the case of high frequencies and large conductors than when lower frequencies and smaller conductors are employed.

SKIN-EFFECT FACTORS FOR VARIOUS FREQUENCIES AND SIZES OF CONDUCTORS

Wire No	0	00	000	0000	½ in.	¾ in.	1 in.
25-Cycle Factor				1.001	1.003	1.007	1.020
60- " "	1.001	1.002	1.005	1.006	1.008	1.040	1.111
133- " "	1.008	1.010	1.017	1.027	1.039	1.156	1.397

The skin-effect factor by which the ohmic resistance is to be multiplied to obtain the virtual resistance for different sizes of conductors and frequencies is as given in the table. Let us assume that a transmission line of number 00 wire and operating at a frequency of 60 cycles per second has a resistance of 75 ohms. If this line be carrying alternating current instead of direct current, the virtual resistance is not 75 ohms but 75 times 1.002 or 75.15 ohms. In a like manner, should the frequency be increased to 133 cycles, the virtual resistance would be 75 times 1.010 or 75.75 ohms; 1.002 and 1.010 are skin-effect factors for 60 and 133 cycles per second respectively, as given in the table.

Alternating-Current Laws

As in the case of direct-current work, certain fundamental laws exist, which are presented, at this point, to enable the student to understand more readily the following discussions. From a review of Ohm's law, as applied to direct currents, Chapter I, we find that the current flow through any circuit containing ohmic resistance is equal to the quotient obtained by dividing the electromotive force in volts by the resistance in ohms. Where, however, inductance or capacity, or both, are involved, the actual resistance to the flow of current is in excess of that offered by the ohmic resistance and the skin effect, unless the existing inductance and capacity are of such value as to neutralize one another. Under such conditions, a modified form of Ohm's law, generally termed "Ohm's law for alternating-current circuits" is employed. This law states that the effective current in amperes is equal to the quotient obtained by dividing the effective electromotive force in volts, by the square root of the sum of the square of the resistance in ohms and the square of the reactance, also in ohms, and may be represented by the following formula:

$$I = E \div \sqrt{R^2 + X^2}$$

also

$$E = I \sqrt{R^2 + X^2}$$

I is the effective current in amperes produced by an effective electromotive force of E volts acting on a circuit of which the resistance is R ohms and the reactance, that is, the combined effect of inductance and capacity is X ohms.

Another law, that of Joule, reads that P is equal to RI^2, in which P is the power expended in watts in heating a circuit of R ohms resistance through which an effective current of I amperes flows.

Kirchoff's First Law

Kirchoff's laws of alternating- current circuits deal primarily with the composition and resolution of electromotive forces and currents, the first of which states that "when an alternating-current circuit branches, the effective current in the main circuit is the geometric (as

in the case of parallelogram of forces) or vector sum of the effective currents in the separate branches."

Shown at A, Fig. 84, is an elementary diagram of connections of a direct-current generator, delivering current to two receiving circuits connected in parallel between the mains of the machines. The current flow through the mains at any instant is equal to the sum of the currents flowing through each of the branches, so

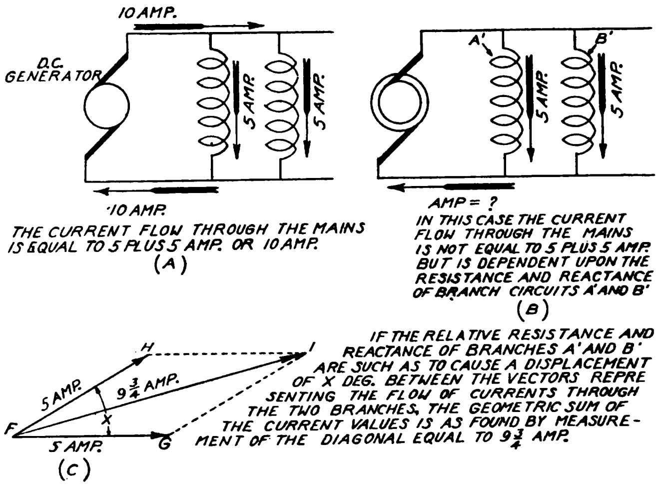


FIG. 84. GRAPHICAL ILLUSTRATION OF KIRCHOFF'S FIRST LAW OF ALTERNATING-CURRENT CIRCUITS

that if upon measurement, it is found that 5 amp. of current are passing through each branch, we know at once that the current flow through the mains is equal to 5 + 5 or 10 amp.

Such is, however, not the case with alternating-current circuits, for due to the presence of inductance and capacity (that is reactance), the maximum values of the current waves will not be reached simultaneously. In other words, an angular displacement as shown at C, Fig. 84, occurs. The value of this angular displacement represented by angle X is dependent upon the value of the resistance and the reactance of each of the branch circuits.

Knowing the value of this angular displacement and the number of amperes of current flowing through each of branches A^1 and B^1, the value of the current in the main may be determined by graphical means as shown at C, Fig. 84.

Letting some unit of measurement, as for example, 1 in. represent the value of 1 amp. of current, lay off horizontal line *FG* 5 in. long (to represent 5 amp.). Then, at an angle of *X* degrees, to *FG*, draw *FH* also

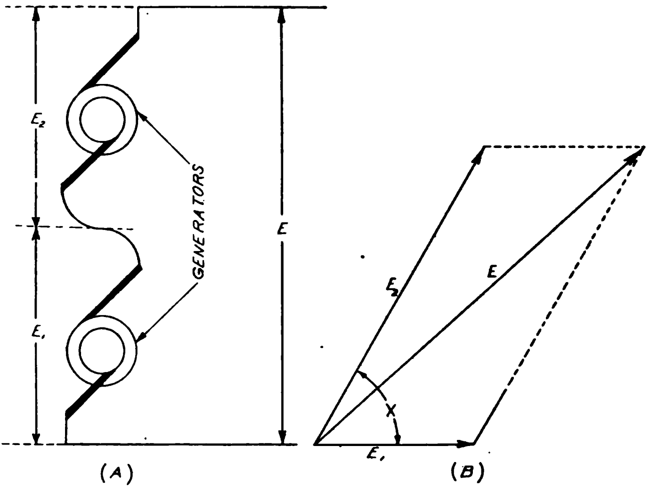


FIG. 85. WHEN TWO ALTERNATORS ARE CONNECTED IN SERIES THE TOTAL EFFECTIVE ELECTROMOTIVE FORCE IS THE VECTOR SUM OF THE EFFECTIVE ELECTROMOTIVE FORCES OF THE INDIVIDUAL ALTERNATORS

5 in. in length and complete the parallelogram by drawing *HI* parallel to *FG*, and *GI* parallel to *FH*. Diagonal *FI* represents the value of the current flow through the main and upon measurement is found to have a length of 9¾ in., thus indicating a flow of 9¾ amp. through the main.

Kirchoff's Second Law

Kirchoff's second law is of two parts and follows:

(a) When two or more sources of alternating-current supply (such as alternators or transformers) are

connected in series, the total effective electromotive force is the geometric or vector sum of the effective electromotive forces of the individual alternators.

(b) When an alternating electromotive force, E, acts upon a number of current-consuming elements or devices connected in series, it is subdivided into parts, each of which acts upon one of the elements and the geometric or vector sum of these parts is equal to E.

As an example of case (a) we have shown in Fig. 85 two alternating-current generators connected in series.

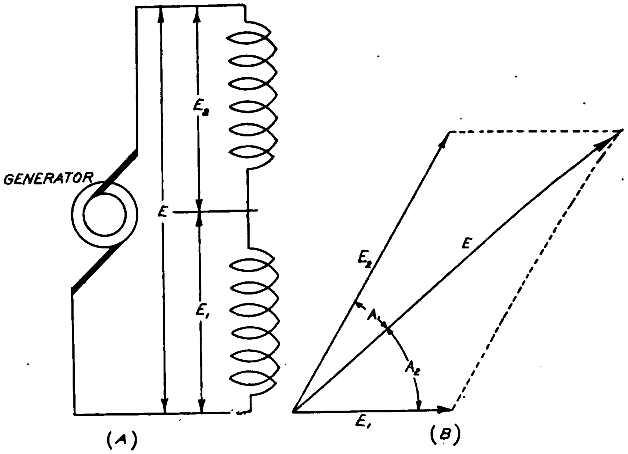


FIG. 86. E, THE ELECTROMOTIVE FORCE ACROSS THE MACHINE TERMINALS, IS EQUAL TO THE VECTOR SUM OF E_1 AND E_2

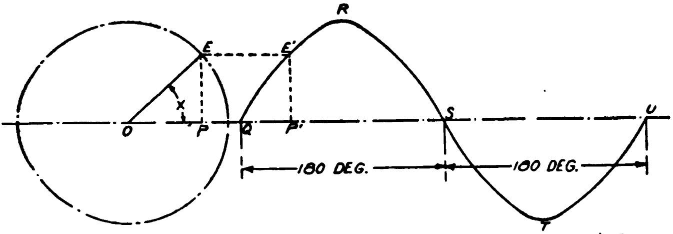
The total electromotive force across the mains is not equal to E_1 plus E_2, but is equal to the geometric or vector sum of E_1 and E_2 *as* indicated at B, Fig. 85; the value of angle X depends upon the positions of the armature coils in the machines relative to their respective field magnets.

The parallelogram of electromotive forces shown at B, Fig. 86, is constructed as at C, Fig. 84, and the value of E, the diagonal, is determined as in that instance.

Where an alternator supplies current to two receiving circuits connected in series the electromotive force

is resolved into two components E_1 and E_2, the values of which depend upon the relative resistance and reactance of the respective coils. As may be seen by reference to Fig. 86 the arithmetical value of E_1 plus E_2 is greater than the value of E.

Where current and electromotive force follow the path of a sine wave, that is, in the case of sinusoidal currents and voltages, and where only resistance is encountered, the current at any instant is proportional to the instantaneous value of the impressed electromotive force. By plotting the instantaneous value of such an



EP IS THE SINE OF ANGLE X AND THEREFORE REPRESENTS AS INDICATED BY ITS PROJECTION, THE ORDINATE E'P' THE INSTANTANEOUS VALUE OF THE ELECTROMOTIVE FORCE — OE IS A VECTOR REPRESENTING THE MAXIMUM ELECTROMOTIVE FORCE WHICH IN MAKING ONE REVOLUTION DESCRIBES (BY PROJECTION OF THE SINE OF ANGLE X) THE SINE CURVE QRSTU

FIG. 87. FOR THE DEVELOPMENT OF ONE POSITIVE AND ONE NEGATIVE WAVE, *OE* MUST MAKE ONE COMPLETE REVOLUTION

electromotive force and current it will be seen that their respective waves pass through zero and reach their maximum values at the same instant. They are said to be in phase.

In the construction of the sine curve as exemplified in Fig. 87, it is evident that for the development of one positive and one negative wave the vector (radius) representing the maximum electromotive force must complete one revolution and as indicated, the value of any instantaneous electromotive force is equal to the product of the value represented by the vector and the sine of the angle which this makes with the horizontal. Let us assume as shown, the vector OE to be making an angle of X degrees with the horizontal; EP then represents the value of the instantaneous electromotive force or that represented by the ordinate $E^1 P^1$ on the curve.

When OE makes one complete revolution, it is said to have passed through an angle of 360 deg., but, instead of employing the term of 360 deg. it is usual in electrical-engineering parlance to express such a complete revolution in radians, a radian being defined as that angle whose subtended arc has a length equal to the radius of the circle. Such an angle is equal to 57.3 deg., and as there are 360 deg. in a circle there are 2 times 3.1416 radians in a circle. If, therefore, the number of revolutions per second of vector OE, or the frequency, is represented by f and the number of seconds that OE

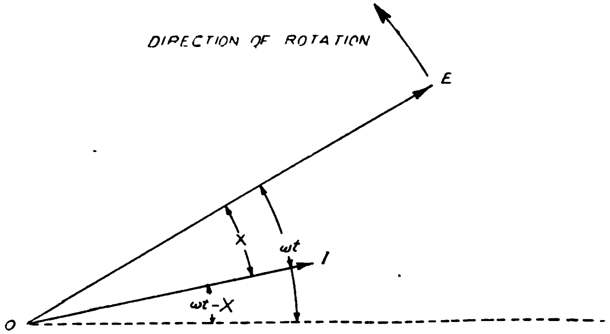


FIG. 88. THE INSTANTANEOUS CURRENT IS EQUAL TO I SIN $(wt\text{-}X)$

rotates by t, then the angle through which OE has passed may be designated by $2 \times 3.1416\ ft$ and as from the above discussion the instantaneous electromotive force is equal to the product of the maximum electromotive force (represented by OE in this case) and the sine of the angle we find any instantaneous value of electromotive force e equal to $E\ max \sin\ (2 \times 3.1416\ ft.)$.

In this equation, as already specified, $E\ max$ is the value of OE, the maximum electromotive force; f is the frequency in cycles per second and t is the time element in seconds.

That part of the foregoing equation represented by $2 \times 3.1416\ f$ may be designated by the letter w so that we have $e = E\ max \sin wt$.

Referring to Fig. 88, we have OE the electromotive force vector at an angle of wt deg. from the horizontal

with OI the current vector lagging behind OE at an angle of X deg. OI therefore is an angle of $(wt - X)$ from the horizontal. From this it is, then, quite evident that the instantaneous current value i, is therefore equal to $I \sin (wt - X)$ where I is the maximum current.

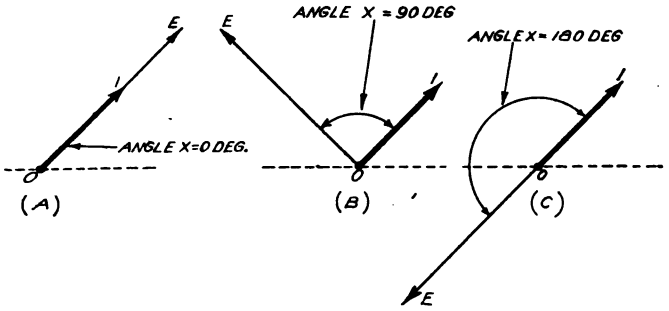


FIG. 89. (A) ELECTROMOTIVE FORCE AND CURRENT IN PHASE
(B) ELECTROMOTIVE FORCE AND CURRENT IN QUADRATURE
(C) ELECTROMOTIVE FORCE AND CURRENT IN OPPOSITION

When angle X is zero, the electromotive force and current are said to be in phase with each other, while when angle X is 90 deg., the electromotive force is zero when the current is at its maximum value, and vice versa. Under these conditions, they are said to be in quadrature with each other.

When angle X is 180 deg., the electromotive force and current are said to be in opposition; they pass through zero simultaneously, but when one is positive the other is negative.

Inductance and Capacity Reactance

Practically, the electromotive force of an alternating-current generator is used to overcome not only resistance but also inductance and in some instances capacity either with or without inductance depending upon the characteristics of the receiving circuit or circuits and cur-

rent-consuming device or devices. Where inductance exists there is also resistance and as they are essentially different in nature and effect it is usual to consider them separately as indicated by the elementary diagram of connections shown at A, Fig. 90. Assuming the current in this circuit to be harmonic, we may represent this graphically by the vector *OI* at B, Fig. 90.

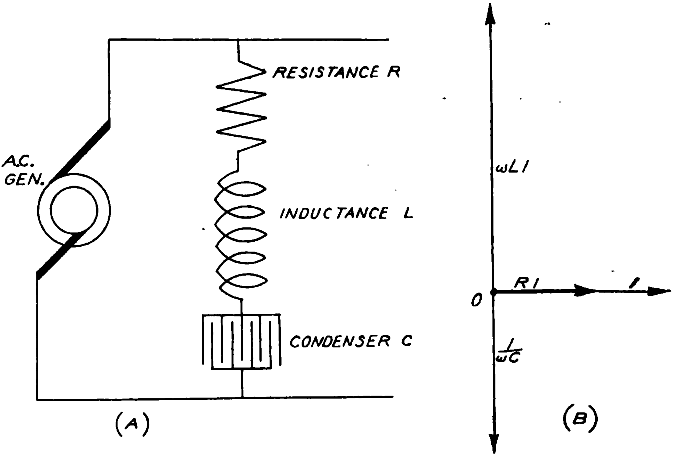


FIG. 90. (A) ELEMENTARY DIAGRAM OF CONNECTIONS OF CIRCUIT CONTAINING RESISTANCE R, INDUCTANCE L AND CAPACITY C

(B) GRAPHICAL REPRESENTATION OF *e.m.f.* RELATIONS IN CIRCUIT SHOWN IN (A)

That part of the electromotive force of an alternator employed to overcome resistance only may, as in the case of direct-current work, be expressed as the product of the current flow in amperes and the resistance in ohms or by RI. This is in phase with the current so may be represented by vector RI, Fig. 90.

As the electromotive force used to overcome the resistance is an alternating electromotive force so is that used to overcome the inductance the effective value of which is $2 \times 3.1416\ f\ LI$ or as $2 \times 3.1416\ f$ is equal to w, by wLI. This is 90 deg. ahead of I in phase and as shown at B, is represented by vector wLI.

That portion of the electromotive force employed to overcome the electro-elasticity of the condenser is 90 deg. behind the current I in phase and has an effective value equal to $I \div 2 \times 3.1416\ fC$ or $I \div wC$. Graphically it is represented by vector downward from O.

As previously stated, the total electromotive force E of the alternating-current generator is used to overcome the resistance, the inductance and the capacity of the connected load. The value of this electromotive force E may readily be determined graphically by the diagram,

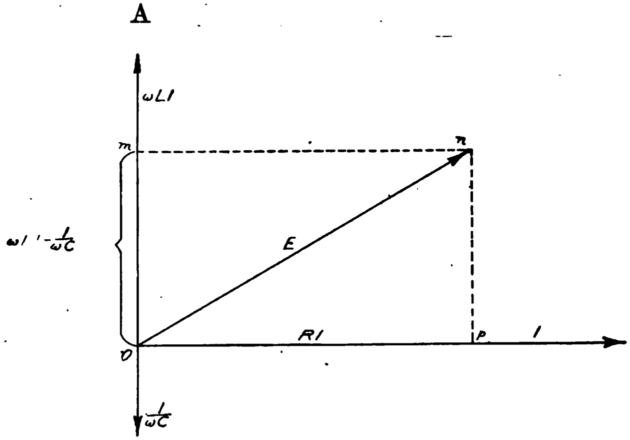


FIG. 91. GRAPHICAL MEANS OF DETERMINING ELECTROMOTIVE FORCE REQUIRED TO OVERCOME THE RESISTANCE, INDUCTANCE AND CAPACITY OF A CIRCUIT AS SHOWN AT (A) FIG. 90

Fig. 91; its resemblance to that shown at B, Fig. 90, is apparent.

The value of E is equal to the vector sum of RI, wLI and $I \div wC$. It is seen that wLI and $I \div wC$ are of opposite sign, so that the sum of wLI and $I \div wC$ is in reality equal to $wLI - (I \div wC)$, which is represented by the vertical vector found by laying off along vector wLI, (OA) from A downward, the value of $I \div wC$, giving $\mathrm{Om} = wLI - (I \div wC)$.

At the end of vector RI is erected perpendicular np equal in length to om. In order therefore to obtain the value of vector sum of RI and $wLI - (I \div wC)$, it is

necessary to determine the value of the diagonal, which being the hypotenuse of triangle onp is equal to the square root of the sum of the squares of op and np or, $on = \sqrt{op^2 + np^2}$. E is, however, equal to on while np is equal to $wLI - (I \div wC)$ and op equal to RI. We have therefore: $E = \sqrt{(RI)^2 + [wLI - (I \div wC)]^2}$ or $E^2 = R^2I^2 + I^2 [wL - (1 \div wC)]^2$ from which $E^2 = I^2 (R^2 + [wL - (1 \div wC]^2)$.

Rearranging and solving for I gives, $I = E \div \sqrt{R^2 + [wL - (1 \div wC)]^2}$ or transposing

$$E = I \sqrt{R^2 + [wL - (1 \div wC)]^2}.$$

The factors wL and $1 \div wC$ are termed the inductance and capacity reactances and when used together

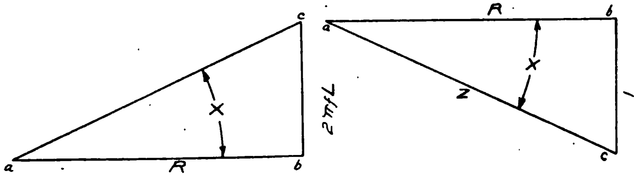


FIG. 92. GRAPHICAL DETERMINATION OF IMPEDANCE OF A CIRCUIT CONTAINING ONLY RESISTANCE AND INDUCTANCE

FIG. 93. GRAPHICAL DETERMINATION OF IMPEDANCE OF A CIRCUIT CONTAINING ONLY CAPACITY AND RESISTANCE

as in the last formula, may be represented by the letter X so that a simplified form of the equation is $E = I\sqrt{R^2 + X^2}$.

For the sake of convenience, the factor $\sqrt{R^2 + X^2}$ is generally termed the impedance and represented by the letter Z or $E = IZ$. In alternating-current work, we therefore have I equal to $E \div Z$ or the quotient obtained by dividing the electromotive force in volts by the impedance, the practical unit of which is the ohm.

The reciprocal of impedance is termed admittance and is obtained by dividing 1 by the impedance in ohms.

Where the circuit under consideration contains only inductance and resistance or only capacity and resistance, the impedance may be graphically determined by means of the diagrams shown in Figs. 92 and 93. To

determine the value of the impedance where only resistance and inductance exist, draw *ab* proportional to *R*, and representing the direction of current flow. At *b* erect perpendicular *bc* proportional to $2 \times 3.1416\ f\ L$, and join *a* and *c* thus giving *ac* representing the impedance of the circuit. Angle *cab*, or *X* is the angle of lag of the current behind the electromotive force while the cosine of angle *X* is the power factor.

The effect of capacity is opposite that due to inductance and as in Fig. 93 where this exists line *ab* is made proportional to *R* but *bc* while perpendicular to *ab* is drawn downward and proportional to the capacity or, $1 \div (2 \times 3.1416\ fC) = 1 \div wC$.

ac then represents impedance *Z* and the current instead of lagging behind the electromotive force leads it by angle *X*.

Resonance

In Fig. 90 is shown resistance *R*, an inductance *L* and a condenser *C* connected in series across the mains of a single-phase alternating-current generator. Let us assume that with the connections as indicated the machine is slowly set in motion although throughout this experiment, adjustment of the field rheostat is such as will provide a constant electromotive force. The inductive reactance may be represented by wL and the capacity reactance by $1 \div wC$, *w* in each being equal to $2 \times 3.1416\ f$. It is therefore evident that where the speed is comparatively low, the frequency *f* is in proportion and as a consequence the value of the inductance reactance, wL, is much less than that of the capacity reactance $1 \div wC$, and as the total net reactance is represented by $wL - (1 \div wC)$ this assumes a negative sign.

With increase of speed, however, (and that of course means increase of frequency *f*), wL will increase in value while $1 \div wC$ will decrease until a certain critical value of frequency *f* is reached when $wL - (1 \div wC)$ becomes zero or wL is equal to $1 \div wC$. We then have $wL = 1 \div wC$, or $w^2 = 1 \div LC$, hence $w = 1 \div \sqrt{LC}$. Since $w = 2 \times 3.1416\ f = 1 \div \sqrt{LC}$,

$$f = 1 \div (6.2832 \sqrt{LC})$$

The unit of capacity for practical work is the microfarad (one millionth of a farad) since circuits seldom have a capacity of more than a few microfarads. If Cm be used to represent the capacity in microfarads, $Cm = 1{,}000{,}000\ C$; and the expression for the frequency for resonance becomes: $wL = 1 \div (wCm \div 1{,}000{,}000)$. $w^2 = 1{,}000{,}000 \div LCm$ and $w = 1000 \div \sqrt{LCm}$.

$$w = 2 \times 3.1416\, f = 1000 \div \sqrt{LCm}, \text{ and}$$

$$f = 1000 \div (6.2832 \sqrt{LCm}).$$

The value of f termed the critical frequency is the frequency at which the inductive reactance neutralizes the capacity reactance.

Further increase of speed (but with the electromotive force still maintained constant) and therefore further increase of frequency, that is beyond the critical value, will result in an increase in inductive reactance wL and a decrease in capacity reactance $1 \div wC$ so that the net reactance assumes a positive value.

By inserting an ammeter in the circuit shown in Fig. 90, it will be noticed that as the frequency increases the current flow increases reaching a maximum value at the critical frequency and then decreases.

This production of maximum current at the critical frequency is termed electrical resonance and may be explained by the fact that as at the critical frequency inductive and capacity reactances neutralize one another, the electromotive force produced is utilized only in overcoming the resistance of the circuit.

Effect of Resonance

Resonant conditions should as far as possible be avoided, as they are conducive to the multiplication of electromotive forces and currents; so-called "piling up" of the voltage may be disastrous to both apparatus and insulation.

Questions on Chapter XI

1. What is the skin effect in conductors? How does it affect current flowing for a given voltage?
2. What is Ohm's law for a.c. circuits?
3. How does reactance affect the value of current? How the value of power?

4. What is Kirchoff's first law?
5. A generator feeds two lines, one taking 25 amperes, and having only resistance; the other taking 40 amperes and having a current lag of 30 deg. What will be the current in the mains? (63 amp.)
6. What will be the power delivered in each line of question 5, if the voltage is 220? (Line 1, 5500 w. Line 2, 7610 w.)
7. What is Kirchoff's second law?
8. In an a.c. circuit the generator armature and line together have a resistance of 5 ohms and a reactance of 1 ohm. The load has a reactance of 10 ohms and a resistance of 10 ohms. With 10 amperes flowing, what will be the voltage drop through generator and line? What voltage will be required on the load? What will be the total voltage to be generated? (1. 50.8 v.; 2. 141.4 v. 3. 185 v.)
9. When are voltage and current in quadrature? When in opposition?
10. The inductance of a circuit is 1 henry; the capacity is 0.0001 farads; the resistance is 200 ohms. When current of a frequency of 25 cycles per second flows; 1—What is the induction reactance? 2—The capacity reactance? 3—The total reactance? 4—The impedance? (1—157.1 ohms. 2—63.5 ohms. 3—93.6 ohms. 4—218 ohms)
11. What voltage will be needed to set up a current of 30 amp. in the circuit of question 10? (6540 volts.)
12. What is inductance? Capacity?
13. How are reactance of induction and capacity related? How does frequency affect them?
14. What is impedance? Of what factors is it made up?
15. What causes resonance?
16. What would be the critical frequency for the circuit of question 10? (15.91 cycles per second.)

CHAPTER XII

ALTERNATING-CURRENT GENERATOR DETAILS

FROM a mechanical standpoint, an alternating-current generator may be one of three types, namely revolving armature, revolving field, or inductor. The first mentioned, as in the case of the ordinary direct-current generator, consists of a stationary structure with inwardly projecting pole pieces, the field, and a revolving member, the armature, which, however, instead of being fitted with a commutator (except in the case of composite wound machines) is provided with two or more collector rings, the number depending upon the type of winding employed. Where this is such as to deliver single-phase current, but two rings are used; where two-phase current, ordinarily four rings; while on three-phase machines at least three rings are required.

MAINTENANCE OF FIELD FLUX

IN DIRECT-CURRENT MACHINES, the field flux is created and maintained by the "excitation" of the windings by a part or all of the current being delivered (this depends upon the type of winding whether series, shunt or compound). But, in alternating-current work, the generator, as its name implies, delivers only alternating current, the characteristics of which do not adapt it to field excitation purposes, and, as a consequence some external source of direct current must be depended upon to provide the excitation required for the maintenance of the necessary voltage. Usually small direct-current generators, either direct-connected or separately driven, are employed, although in many instances storage batteries are utilized, particularly for emergency service, as when for some reason or other the regular source of excitation fails.

In Fig. 94 is shown a diagram of connections, indicating the manner in which the field coils of an alternating-current generator are "excited." As the load on the alternator approaches maximum, the voltage on the outside lines decreases and in order to compensate for this drop, the alternator voltage must be raised. This is accomplished by cutting out some of the resistance of the

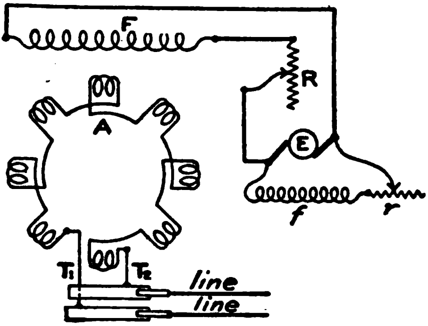


FIG. 7. CONNECTION DIAGRAM OF AN A.C. GENERATOR AND ITS EXCITER

FIG. 94. DIAGRAM OF CONNECTIONS INDICATING MANNER OF EXCITING ALTERNATOR FIELD WINDINGS

alternator field rheostat, which allows an increased flow of current through the field winding. A rheostat is also inserted in the exciter field circuit in order to maintain its voltage at a constant value with varying loads; the greater the current flow through the alternator field winding, the greater the load upon the exciter.

Exciter capacity should usually be about ½ per cent of the alternator capacity for high-speed turbine-driven machines. They should be of a design to give full voltage at low excitation, so that a small change in field current will cause an appreciable change in voltage.

Composite-Wound Machines

In some alternating-current generators, especially those of the smaller capacities, a portion of the current generated is utilized for field excitation purposes, an arrangement which not only allows the use of an exciter of somewhat smaller capacity, but provides a compound-

ing effect. These machines are generally termed composite or compound-wound alternators. The essential features of connections of such a machine are shown in Fig. 95. In addition to the regular winding, the armature shaft carries a small transformer, the primary of which is in series with the armature winding while the secondary as indicated is connected to a rectifier consisting of a commutator mounted on the armature shaft adjacent to the collector rings. The number of segments employed is the same as the number of field

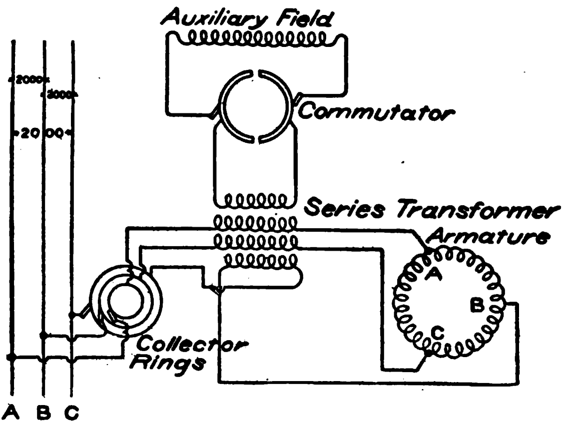


FIG. 95. DIAGRAM OF CONNECTIONS OF COMPOSITE WOUND ALTERNATOR

magnet poles with alternate segments interconnected and each set tied in with the transformer secondary in the manner indicated. With the brushes which bear against the segments of this rectifier given a spacing equal to that between the centers of any two adjacent segments, each negative electromotive force (and current) wave is caused to assume a positive value with the result that the current flow through the machine series winding is unidirectional although pulsating.

Inductor Alternators

Another type of alternating-current generator is the inductor machine, in which both armature and field windings are made stationary, thus eliminating the use

of moving conductors and contact-making devices, such as collector rings and commutators and brushes. Sectional views of a machine of this type are shown in Fig. 96. The structure supporting the armature winding is of ring shape, laminated and with the interior surface slotted for securing the coils, while the revolving member is simply a spider carrying on its periphery

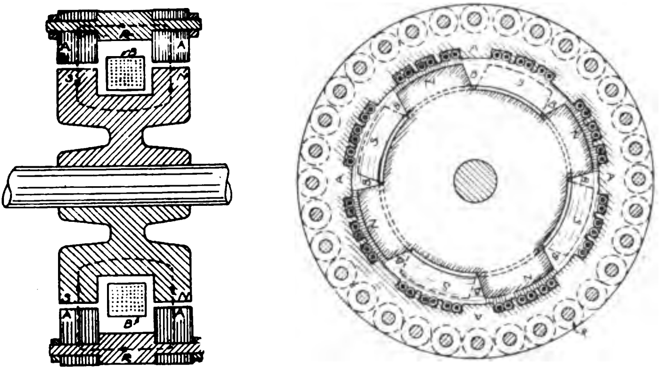


FIG. 96. SECTIONAL VIEW OF INDUCTOR ALTERNATOR

projecting pole pieces N and S which are excited by a circular field coil B. With a flow of direct current through this coil and the revolving member set in motion, a magnetic flux is established and with the sweeping of pole pieces N and S across the face of the armature winding an electromotive force is induced in the regular manner. But few inductor machines are in use today.

Structural Details

In the revolving-field alternator, the type in most general use, a stationary member or stator of the form shown in Fig. 97 is employed. In this particular construction, the frame consists of a pair of iron castings for the support of the armature core which is built up of sheet-iron laminations mounted in the inner periphery of the frame and properly lapped to make a practically continuous magnetic circuit. These laminations are secured by through bolts and are held in place by the clamping action of the frame castings.

Construction of the revolving field is shown in Figs. 98 and 99. Cores of the field poles are supported by a

FIG. 97. STATIONARY MEMBER, OR STATOR, OF REVOLVING FIELD ALTERNATOR

spider made up of sheet iron laminations and are built up from punchings also of laminated steel assembled under pressure between malleable iron or steel end plates and are then riveted together.

FIG. 98. SHAFT, REVOLVING FIELD CORE, POLE PIECE AND STEEL KEYS

On the pole cores is placed insulation over which the coils are wound. Collectors are bolted to a cast-iron ring pressed on the shaft, a form of construction insuring ample ventilation, high insulation and ready access. Armature coils are held in place by wooden wedges.

FIG. 99. FIELD COIL IN VARIOUS STAGES OF CONSTRUCTION

Some of these machines are fitted with individual exciters with armature mounted on the shaft carrying the alternator rotating members; this provides against loss of excitation due to failure of a separate driving motor or engine.

FIG. 100. TYPICAL 3-PHASE ALTERNATOR OF BELTED TYPE

Alternator Armature Windings

THE WINDINGS of alternating-current generator armatures are, as will be noted by the various diagrams of connections, much less complicated than those of direct-current machines, and may be either of the concentrated

or distributed form. Where all of the wires on the armature are grouped in P slots, where P is the number of field magnet poles, the winding is said to be concentrated while the wires spread out in P similar groups of slots, where P is again the number of field poles, the

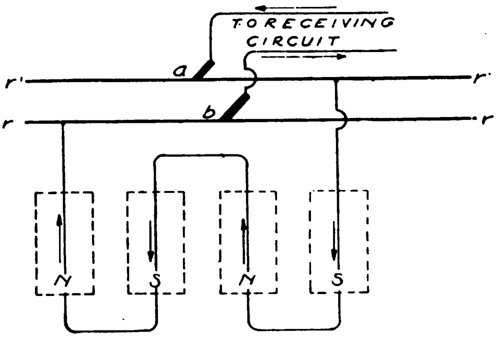


FIG. 101. A SIMPLE CONCENTRATED ARMATURE WINDING

winding is termed distributed. As may be quite readily understood from a study of Fig. 101, which shows a simple and concentrated-winding, the electromotive force induced in the conductors has a tendency to rise suddenly in value as the slots come under the pole pieces and to fall quite as suddenly as the slots leave the pole

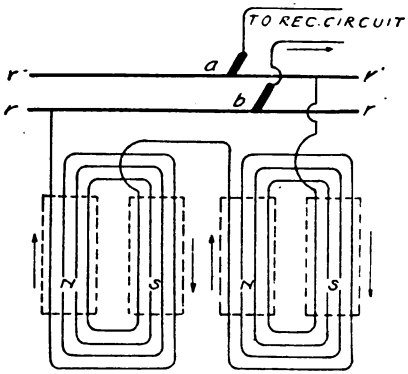


FIG. 102. SIMPLE DISTRIBUTED ARMATURE WINDING

pieces. This is, however, not the case with the distributed form of winding, Fig. 102, for with this, due to the greater portion of periphery covered by each coil, the rise and fall of the electromotive force is more gradual.

Questions of Chapter XII

1. What three types of alternating-current generators are in use?
2. What is the difference between single-phase, two-phase and three-phase machines?
3. How are alternators excited?
4. What is a composite-wound alternator?
5. What capacity exciter would you buy for a 500 kw. alternator?
6. Make a good sized sketch for the complete connections, showing the exciter of a two-phase composite-wound alternator.
7. Why are the field poles laminated in an alternator?
8. What is the advantage of distributed armature coils over concentrated coils?

CHAPTER XIII

POLYPHASE SYSTEMS

Two and Three-Phase Windings

SINGLE-PHASE alternating current is today employed to but a limited extent for other than lighting service and as the majority of electric systems with their connected transforming devices and power-consuming apparatus use polyphase alternating current, it is desirable to pay some attention to the polyphase system. Although theoretically any number of phases may be employed commercially, only two and three-phase systems are in use and while upon the introduction of the induction motor, two-phase systems rapidly supplanted the single-phase, these have in turn been superseded by the three-phase system with its lesser copper requirements for transmission lines. Except for special service, the three-phase is the most widely used.

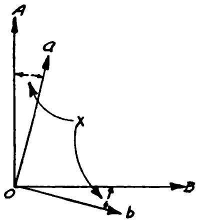
Two Phase

For the generation of two-phase currents, two electrically, although not mechanically, distinct armature windings are provided and so placed relatively one to the other that their electromotive forces and currents are displaced by 90 deg. or as is generally termed, are in quadrature. The diagram, Fig. 103, is illustrative of this.

Vector OA represents the electromotive force in phase A while at 90 deg. is vector OB representing the electromotive force of phase B. Ordinarily where the currents of the two phases are of equal value and supply circuits of like power factor, vectors Oa and Ob, representing the value of the currents in phases A and B respectively, are of equal length and lag behind (or where capacity predominates lead) vectors OA and OB by equal amounts. The degree of lag may be represented by any desired angle, as X, although the actual value of

this angle is dependent upon the power factor of the circuits supplied with current.

The armature leads of any two-phase machines of the stationary armature type may be either three or four in number. When but three are utilized, one of the leads is employed as a common return for the other



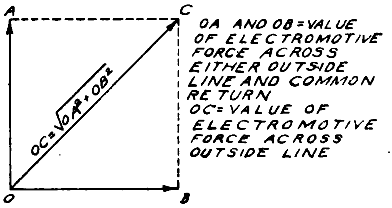


FIG. 103. ELECTROMOTIVE FORCE AND CURRENT RELATIONS OF A 2-PHASE ALTERNATOR

FIG. 104. ELECTROMOTIVE FORCE RELATIONS OF A 2-PHASE 3-WIRE SYSTEM

two and the current flow through such a common return line is at any instant equal to the square root of the sum of the squares of the other two instantaneous current values. Similarly the electromotive force across the two outside lines is equal to the square root of the sum of the squares of the instantaneous electromotive force values across the common return lead and the two outside lines.

Three-Phase Currents

With the more general use of alternating current, especially for power service, long-distance transmission systems and more extensive distribution systems became necessary. Economy of construction was, however, of vital importance and as a conisderably larger amount of copper (and also of line fittings as cross arms, brackets, insulators, insulator pipes, etc.) was required to transmit a given amount of power over a four-wire two-phase system than over a three-wire three-phase system, the latter proved more desirable and as a result, the three-phase alternating-current generator rapidly displaced the two-phase machine.

Let E represent the voltage across any two lines at the receiving end of either a two-phase or a three-phase system; R_2 the resistance of each of the four wires of a two-phase system; and I_2 the current flow in amperes in any one line of a two-phase system. The power in watts is then equal to $2EI_2$ while the line loss in watts may be represented by $4R_2I_2^2$.

With I_3 and R_3 designating respectively the current flow and the resistance for each conductor of a three-phase system delivering the same amount of power as the two-phase this power expressed in watts is equal to $\sqrt{3}\ EI_3$ (assuming unity power factor in each case) and the loss in watts to $3R_3I_3^2$. $\sqrt{3}\ EI_3$ is, however, equal to $2EI_2$ or, cancelling E from each side of the equation, I_2 is equal to $\sqrt{3}\ I_3 \div 2$.

If the power losses are also equal, $4R_2I_2^2 = 3R_3I_3^2$; but, as I_2 is equal to $\sqrt{3}\ I_3 \div 2$ we have

$$4R_2\left(\frac{\sqrt{3}I_3}{2}\right)^2 = 3R_3I_3^2$$

a formula which upon simplification resolves itself into the form $R_2 = R_3$, thus revealing the fact that each wire of each system has the same resistance and is of the same weight. It is therefore apparent that with a given amount of delivered power the two-phase system requires 4/3 times as much copper as the three-phase. In other words, the copper cost of a three-phase system is 75 per cent of that of a two-phase 4-wire system.

Three-Phase generators

Let us assume Fig. 105 to represent part of the field structure of an alternating current generator together with a section of the armature and its windings, consisting of coils 1, 2 and 3 joined to other members of like sets and terminating in three collector rings. Each of the armature coils, as may be seen by reference to Fig. 105, is placed in slots so spaced as to bridge the polar pitch of the machine, that is, when the center line of any one coil coincides with the center of any pole

piece the center line of the other side of the coil will coincide with the center of the adjacent pole piece. Between the slots of any given coil, however, are two other equally spaced slots each carrying other coils so that, as the armature revolves, coils 1, 2 and 3 pass

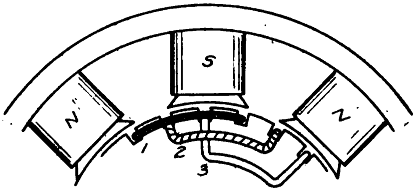


FIG. 105. RELATIVE POSITIONS OF ARMATURE COILS IN A THREE-PHASE GENERATOR

successively under the pole pieces with the result that electromotive forces are induced within the windings which, due to the relative positions of the coils with reference to each other, are displaced as shown in Fig. 106 by 60 electrical degrees.

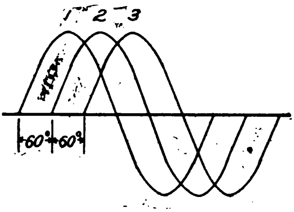


FIG. 106. INTERNAL ELECTROMOTIVE FORCE CURVES OF A THREE-PHASE GENERATOR

With this arrangement, however, it is evident that like electromotive force (and current) values occur so as to form peak periods, a condition not conducive to the satisfactory operation of many kinds of current consuming devices. In order to overcome this, it is usual therefore to reverse the terminal connections of phase 2 thus reversing the phase of its electromotive force with respect to the other lines and obtaining a set of electromotive

force curves as shown in Fig. 107, corresponding values of which are at all times displaced by 120 electrical degrees. This displacement of electromotive force phase exists, however, only outside of the machine; within the machine, it is as shown in Fig. 106.

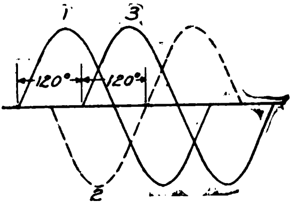


FIG. 107. ELECTROMOTIVE FORCE CURVE DUE TO PHASE WINDING 2 CONNECTION REVERSED

As a rule, winding connections are made within the generator and but three leads brought to the terminal board. In making these internal connections, one of two schemes may be employed: they may be either of the delta or mesh form as shown at A, Fig. 109, or of the Y or star form, B Fig. 109.

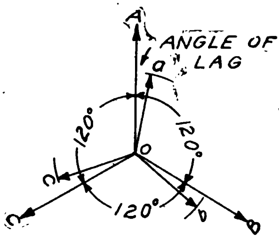


FIG. 108. ELECTROMOTIVE FORCE AND CURRENT RELATIONS OF A THREE-PHASE SYSTEM

With either form of winding, the electromotive force and current relations may be shown vectorially, as in Fig. 108, wherein vectors OA, OB and OC, each 120 deg. apart, represent electromotive force values while vectors Oa, Ob and Oc, shown lagging behind OA, OB and OC, represent current values. The degree of angle

of lag (or lead when capacity predominates) is dependent upon the power factor; with unity power factor, Oa will coincide with OA, Ob with OB and Oc with OC.

While in the delta scheme of connections, the voltage across the mains, E′, as indicated at A, Fig. 109, is identical to the phase voltage that is equal to that across

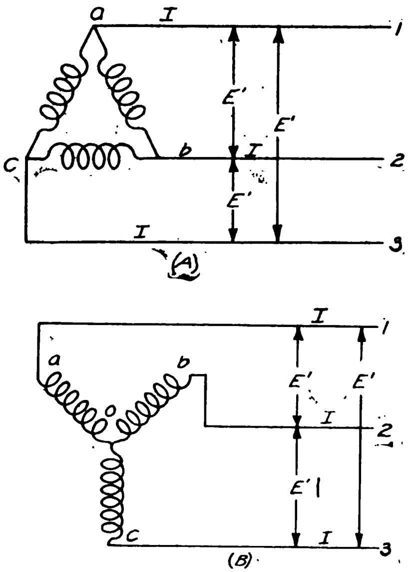


FIG. 109. ILLUSTRATING DELTA OR MESH AND Y OR STAR ARMATURE WINDING CONNECTIONS

windings ab, bc or ca, such is not the case where the Y system is employed. Voltage E′ across any two lines, B Fig. 109, where the voltage across any one of these windings may be designated by e, E′ is equal to $e\sqrt{3}$. This is due to the fact that E′ is equal to the vector sum of the voltages of any two windings as for example, line voltage E′ across mains 2 and 3 is equal to the vector sum or resultant of voltages across ob and oc.

In the Y scheme, however, the line current I is equal to the current flow through any winding. With the delta connection, because of the fact that the current flow through any line is at any instant equal to the

vector sum of the current flow through any two windings, the line current I is equal to $i\sqrt{3}$ where i is the current flow in amperes through any one winding.

Where e and i represent the volts and amperes of each armature phase respectively, it is evident that in each phase the power in watts is equal to $e \times i \times$ p. f. where p. f. is the power factor expressed as a decimal. But, in the Y connected armature, E′ is equal to $e\sqrt{3}$ and i is equal to I while in the delta scheme, I is equal to $i\sqrt{3}$ and E′ to e. As a consequence, the power in watts may be represented by the equation $W = \sqrt{3}\ EI \times$ p. f. where W represents the number of watts carried by the 3-phase circuit.

Questions on Chapter XIII

1. If current in each phase of a two-phase, three-wire circuit is 100 amperes, what will be the current in the common return? (141.4 amp.)
2. For 220 volts per phase of a two-phase three-wire system, what will be the voltage across the outside wires? (310 v.)
3. Why are 3-phase ssytems most commonly used?
4. How are the coils on a 3-phase armature spaced?
5. How is the 120 deg. phase secured in the transmission line?
6. What is the star system of connection? The delta?
7. If the e.m.f. per armature phase is 1000, what will the voltage on the 3-phase transmission line be for a delta connected system? For a star connected system? (1000) (1732.)
8. What will be the power transmitted in each case if the current per line wire is 20 amp. and the power factor 90 per cent? (For delta, 31,176 watts.) (For star, 54,000 watts.)

CHAPTER XIV

VOLTAGE REGULATION OF ALTERNATING-CURRENT GENERATORS

Alternator Systems for One and for Several Machines

REGULATION of a constant-potential alternating-current generator may be defined as the per cent change in voltage (based on full-load voltage and at constant speed and excitation) occurring when under given power factor conditions the load is changed from full load to no load. This may be explained more fully by citing a typical example. Let us assume that under full load the terminal voltage of a machine is 220 v., while as soon as the main switch is opened the voltage rises to 230 v. This is an increase of 10 v. above that at full load. Dividing 10 by 220, we obtain as a quotient 0.045, or 4.5 per cent, the regulation of the machine under the specified conditions.

If, however, the power factor of the receiving circuit is high, regulation is better, (less drop from no load to full load); and if the capacity effect of the circuit is in excess of the inductance effect, the voltage of the machine instead of rising with a release of load will tend to drop; that is, where the full-load voltage as before is 220 v., sufficient capacity in the receiving circuit may cause a drop in voltage to 210 v. as soon as the main switch is opened. As before, the change in voltage is 10 v. and while the regulation remains 4.5 per cent this assumes a negative value more properly expressed as a negative regulation of 4.5 per cent.

Control of Voltage

Where the current generated is used primarily for the operation of lighting units, load changes occur more gradually than in installations in which the load is in whole or in part made up of electric motors, frequently carrying variable and abruptly changing loads. Where

the former conditions exist, regulation changes are gradual and voltage control may satisfactorily be accomplished by manual operation of the generator's field rheostat or the shunt field rheostat of the exciter, or both. With but one generator and one exciter installed, both rheostats may be operated without harm; although it is preferable, especially where a single exciter is used to serve two or more generators, to use the exciter field rheostat only to maintain proper exciter voltage and the

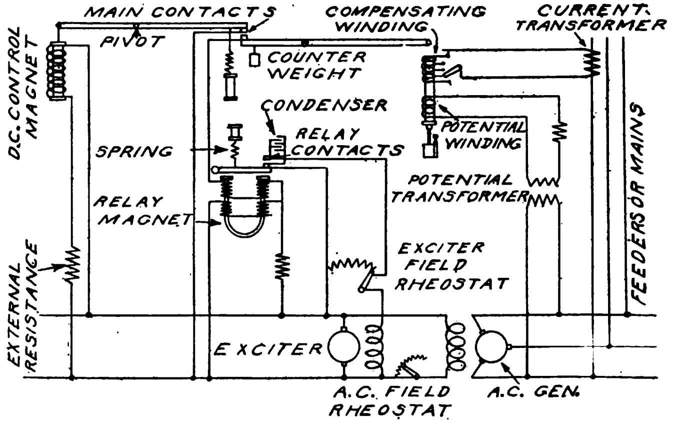


FIG. 110. ELEMENTARY CONNECTIONS, TIRRILL VOLTAGE REGULATOR USED WITH 3-PHASE GENERATOR

generator rheostat for the control of the generator bus voltage.

Few plants are, however, employed for lighting service only and with the large generating units now in use, supplying current to hundreds of motors with their various characteristics and changing loads, it would be a physical impossibility to provide a satisfactory terminal voltage without the use of some form of automatic device.

Automatic Regulator

There are two general methods of automatic voltage regulation. In the first, as used in the Thury regulator, the field resistance is automatically adjusted by motors

or solenoids controlled by a relay; in the second method, which is that employed in the Tirrill regulator, a resistance is alternately cut into and out of the generator field circuit. The essential parts of the regulator, see Fig. 110, are a direct-current control magnet, an alternating current control magnet and a relay. The first-mentioned, which has a fixed stopped core in the bottom and a movable core in the top, is connected directly across the exciter bus bars; the movable core is attached

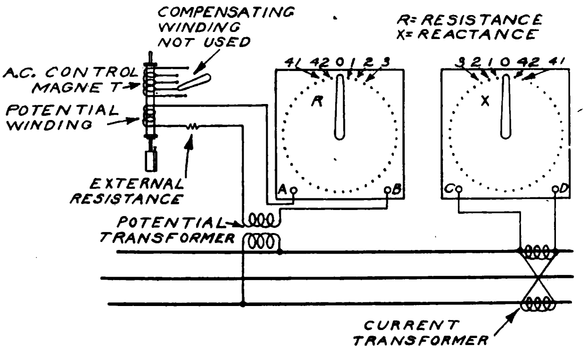


FIG. 111. METHOD OF CONNECTING LINE DROP COMPENSATOR

to a pivoted lever having a flexible contact capable of being pulled downward by helical springs. Opposite this is a second pivoted lever having at one end a contact and counterweight and at the other end a movable core under the influence of an alternating-current control coil, consisting of a potential winding connected to the main generator bus bars through a potential transformer and an adjustable compensating winding connected through a current transformer to the main lighting feeder.

The U-shaped relay magnet is provided with a differential winding, both sections of which, like the direct-current control magnet, are connected across the exciter bus; one of these sections is connected direct while the other is connected through the main contacts. The armature used with this relay forms a means of short-circuiting the exciter field rheostat through contacts pro-

vided for the purpose; condensers connected across these contacts prevent destructive arcing.

Where the system fed has a variable power factor, better results are obtained by eliminating the compensating winding and employing a line drop compensator. This consists of an adjustable resistance and reactance connected as shown in Fig. 111.

When, due to excessive load or otherwise, the main bus voltage is below normal, the weight of the core of

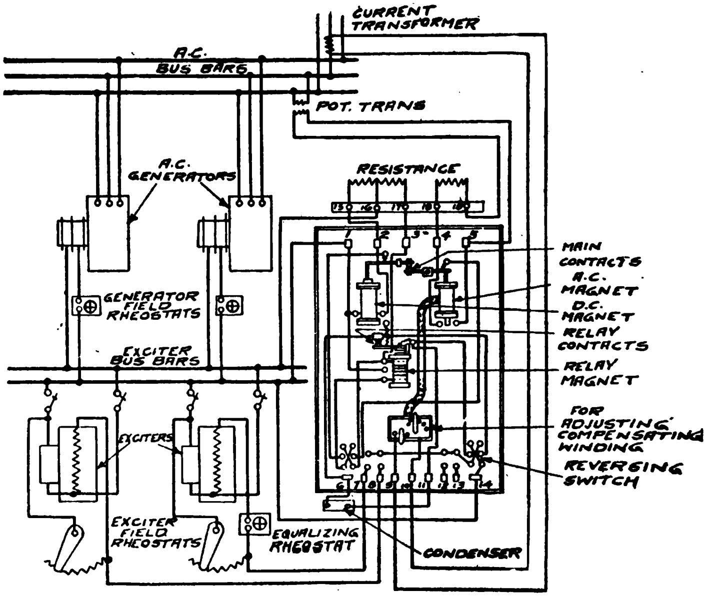


FIG. 112. VOLTAGE REGULATOR CONNECTIONS FOR PARALLEL OPERATED A. C. GENERATORS AND EXCITERS

the alternating-current control magnet overcomes that of the counterweight and closes the main contacts, causing the relay magnet to act upon its armature and close the relay contacts. This short-circuits the exciter field rheostat, raising the exciter voltage and in turn the generator voltage. As soon as the exciter voltage is increased, the direct-current control magnet exerts a greater pull upon its core, which, being attached to the

pivoted lever, raises the upper main contact; and with the bus voltage below normal, the lower contact follows. As the bus voltage, however, approaches its normal value, the main contacts are opened, the relay magnet is caused to release its armature, the relay contacts are opened and the exciter resistance is again cut into circuit. Due to the sensitiveness of the magnets, this operation is continued at a high rate of vibration and, as a result, a pulsating exciter voltage of the required value is maintained.

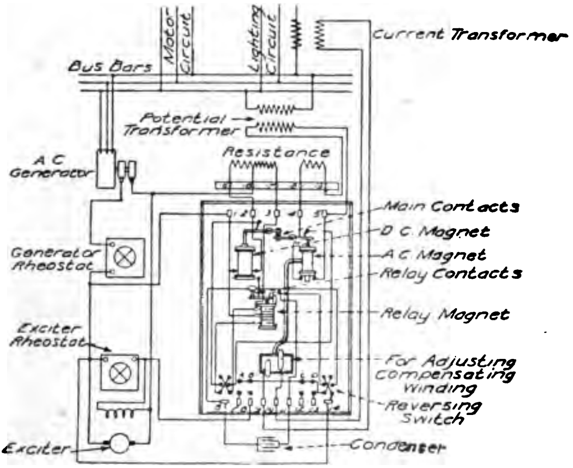


FIG. 113. VOLTAGE REGULATOR CONNECTIONS FOR ONE OR MORE A. C. GENERATORS AND ONE EXCITER

AUTOMATIC REGULATION OF VOLTAGE

ADVANTAGES due to the use of automatic voltage regulators with alternating and direct-current generators and balancer sets on 3-wire direct-current systems may be enumerated as follows: Use of more economical lamps; fewer lamp renewals; conservation of energy; reduction in loss of energy due to lowering of voltage; and reduction in station operating force.

Figures 112 and 113 are diagrams of connections of a voltage regulator used in connection with parallel operated generators and exciters, and of a regulator em-

ployed with one or more generators using one exciter, respectively.

Regulation with Constant Exciter Voltage

Station auxilliary light and power equipment is frequently dependent upon some source of direct current and as frequently the exciters are the only direct-current generators in the plant, the Tirrill regulator as ordinarily applied cannot be employed without variation of the exciter bus voltage. For such installations,

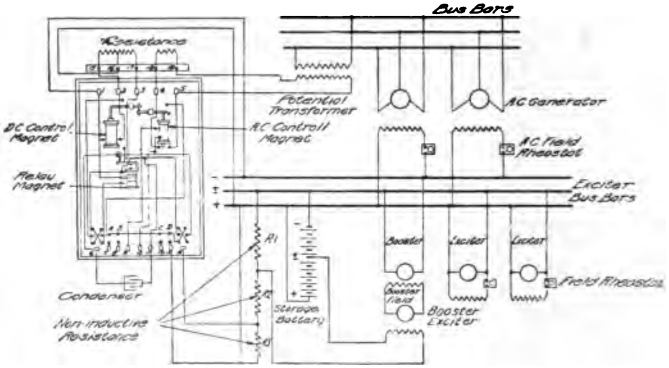


FIG. 114. REGULATOR CONNECTIONS WHERE 2 PARALLEL OPERATED EXCITERS ARE EMPLOYED IN CONNECTION WITH STORAGE BATTERY AND BOOSTER

the following scheme has been devised and developed by the General Electric Co.

A booster is inserted, as shown in Fig. 114, between the bus and the fields of the alternating-current generators The field of this booster is separately excited by means of a small exciter which, in turn, has its fields excited from the difference in potential between a point on either a resistance connected across the exciter bus, or where a storage battery is employed, the middle tap of this battery, and a point of variable potential on a series of three resistances. These are connected across the exciter bus so that the booster may be excited with either polarity as required.

The regulator is connected across one resistance R-3 which is equal to about 4 times resistance R-1; resistance R-1 is equal to twice that of R-2. Should, therefore, resistance R-3 be short-circuited by the regulator, resistance R-1 being twice R-2, the current flows in a

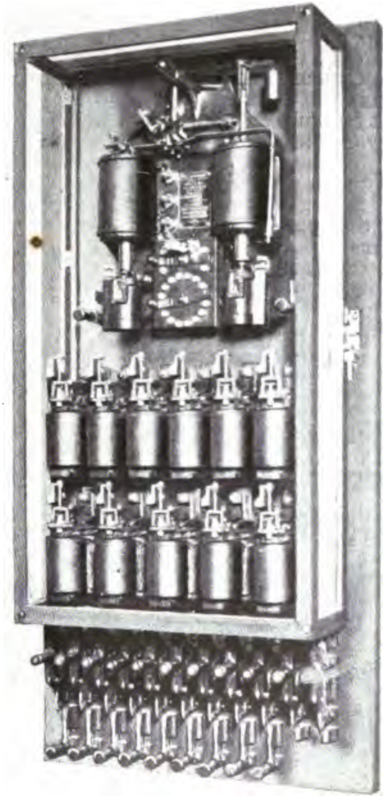


FIG. 115. WESTINGHOUSE TYPE AC-9 GENERATOR VOLTAGE REGULATOR

direction to boost the voltage. Should the contacts remain open, resistance R-3 is inserted; the sum of R-3 and R-2 is greater than R-1, and the current in the booster field flows in the reverse direction, causing the

booster to oppose the exciter voltage. This cycle of operation being repeated very rapidly, a constant voltage is maintained on the alternating-current generator bus.

WESTINGHOUSE GENERATOR VOLTAGE REGULATORS

IN THE voltage regulator built by the Westinghouse Electric & Mfg. Co., the main control magnet is energized entirely by alternating current supplied by the

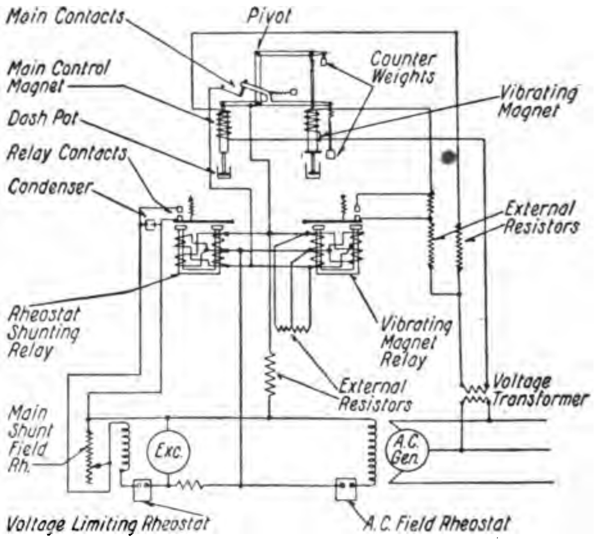


FIG. 116. SCHEMATIC DIAGRAM OF WESTINGHOUSE TYPE AB-1 REGULATOR

system being regulated, an arrangement said to free the regulator from the lagging influence of the exciter system and to eliminate the necessity of paralleling the exciters. Other features claimed for this regulator are its ability to handle an unlimited station capacity on a single control element, and its satisfactory operation on systems where extreme range of exciter voltage may be required.

As may be seen by referring to the schematic diagram of connections, Fig. 116, this regulator consists

of a main control magnet, a vibrating magnet, a set of main contacts and two relays. The main control and vibrating magnets are of the solenoid type, are exceedingly sensitive and are provided with dashpots to permit adjustment of regulation to suit the characteristics of the system. Below these magnets are placed the two relays, the one at the right, the vibrating relay being used to govern the operation of the vibrating magnet; the one at the left is the rheostat shunting relay. Regulators of large size are provided with one or more master relays which control a group of rheostat shunting relays, thereby relieving the main contacts of handling control currents beyond their capacity.

The upper end of the core stem of the main control magnet is connected to one end of a counterweighted floating lever supported by a bell crank lever pivoted to the frame of the regulator as shown; the upper end of the core stem of the vibrating magnet is attached to the horizontal arm of this bell crank lever through the medium of a spiral spring. A counter weight is suspended at the extremity of this arm. Both main control and vibrating magnets are energized by the same voltage transformer, and actuate the movable main contact into and out of engagement with the fixed contact.

Due to the unique underlying principle of operation employed, a description of this may best be presented by quoting in substance from literature issued by the Westinghouse Company on the subject. An inspection of schematic diagram, Fig. 116, shows that the closure of the main contacts causes all relay contacts to close. The vibrating relay is connected so that the closure of its contacts shunts a small portion of the resistance in series with the vibrating magnet, thus increasing its pull and opening the main contacts. This in turn opens all relay contacts and inserts the full resistance in the vibrating magnet circuit, weakening the pull and closing the main contacts again.

From the above cycle it is seen that for any given position of the floating lever, continuous vibration results. A necessary condition to the continuous vibration of the system is that the weight of the vibrating

magnet core and lever must be exactly balanced by the tension of the control spring, and average pull of the magnet. Any change in the tension of the control spring results in an equal change in the average magnet pull. For a given line voltage there is a definite magnet pull when the contacts are closed, and a definite pull of less value when the contacts are opened. The average magnet pull must be a function of the time of the contact engagement. For any given position of the floating lever there is a corresponding position of the bell crank lever, and tension of the control spring; however, on account of the balanced condition there must be a corresponding average magnet pull and time of contact engagement.

Rheostat-shunting relay contacts open and close across the shunt field rheostat of the exciter, and the effective resistance of the rheostat is determined by the time of contact engagement. For every value of effective resistance there is a corresponding value of exciter voltage, and, therefore, alternating-current voltage.

The time of contact engagements as here used, means the ratio of the time the contacts are closed to the total time for opening and closing.

As the control element is energized from the alternating current generator, the main control magnet will assume a position such that a time of contact engagement is maintained sufficient to develop an exciter voltage and, therefore, an alternating-current voltage capable of balancing the core weight. Any variation in line voltage changes the position of the floating lever in such a manner as to vary the excitation and restore the balance.

For self-excited direct-current generators, the rheostat shunting relays operate directly on the generator field rheostats, the control system being actuated from the direct-current mains through a suitable resistance. For direct-current machines having a separate exciter, the rheostat-shunting relays operate on the exciter rheostat the same as in the alternating-current regulators.

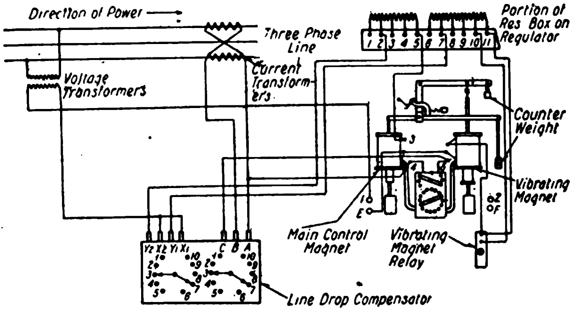
In the standard-range regulator, the rheostat shunting relays are energized from the exciter circuit; but in the broad-range regulator rheostat shunting, vibrating

and master relays are energized from an independent source of direct current.

In Fig. 117 is shown a diagram of connections of Westinghouse regulator and external compensator for 3-phase systems.

Excess Voltage Protection

Unless regulators of the types described are protected by some form of cutout relay or protective device, accidents such as are bound to arise in the operation



The above connections are correct for a secondary operating voltage of 110 Volts. If a different operating voltage is required, refer to the internal diagram of connections of the regulator for the proper connections to the external resistor

FIG. 117. CONNECTIONS OF REGULATOR AND EXTERNAL COMPENSATOR FOR 3-PHASE SYSTEMS

of electric distribution systems may be the cause of much poor service and trouble due to an abnormal rise of voltage. An accident to the regulator may cause the relay contacts to stick and produce an exceedingly high exciter voltage; when a short circuit on the system is cleared, a dangerous voltage rise is inevitable. When a short circuit occurs and the regulator is not protected, the main contacts will close, causing the relay contacts to close and the exciter voltage to build up to maximum; and when the short circuit is cleared, the high exciter voltage and the accompanying high degree of generator field excitation cause the creation of an abnormal generator voltage which will continue until the regulator has had time to become operative again. Such effects are

detrimental to the service, causing the destruction of lamps, heating devices and motors which at that time may be connected to the system.

Schematic diagrams of two forms of high-voltage cutout relays for use in connection with regulators as built by the General Electric Co. are shown in Figs. 118 and 119. In the former, the control magnet is connected

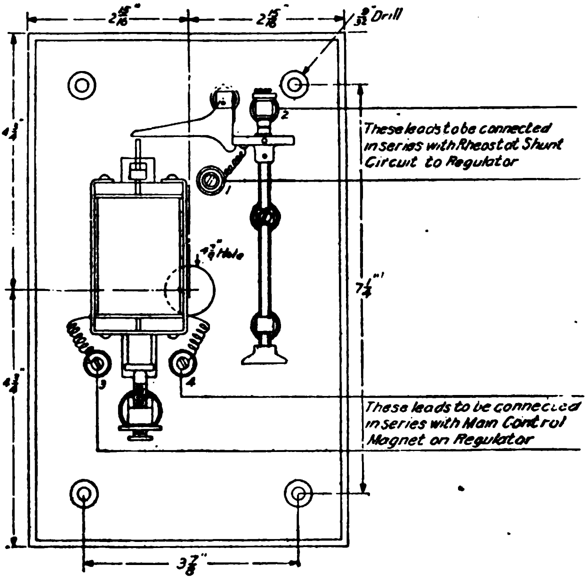


FIG. 118. SCHEMATIC DIAGRAM OF GENERAL ELECTRIC CUT-OUT RELAY WITH MANUAL RESET

in series with the main control magnet of a regulator having but a single relay, and the contacts are connected in series with the rheostat shunt circuit. A rise in voltage in excess of a predetermined value depending upon the setting of the thumbscrew causes the plunger to rise and trip open the contacts, which, opening the rheostat shunt circuit, inserts resistance into the exciter field and thereby reduces the generator voltage.

Excitation for the magnet in Fig. 119 is obtained from a potential transformer or pressure wires; the two

upper contacts are normally closed and as in the case of Fig. 118 are connected in series with the rheostat shunt circuit to the regulator. Upon a sudden rise in voltage, the plunger of the control magnet is drawn upward, resulting in the opening of the upper contacts and the rheostat shunt circuit and a decrease in exciter voltage. The effect of this action is to decrease the

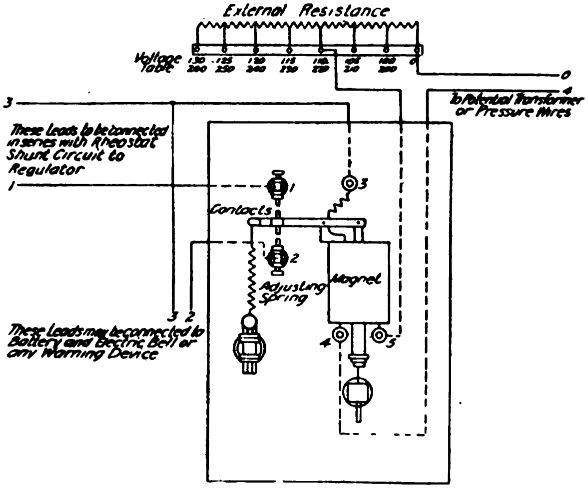


FIG. 119. SCHEMATIC DIAGRAM OF GENERAL ELECTRIC AUTOMATIC REGULATOR CUTOUT RELAY

machine voltage which in turn will allow the control magnet plunger to resume its former position and close the upper contacts. This cycle is then repeated until normal conditions again prevail.

Another regulator protective device as manufactured by the General Electric Co. is that shown diagrammatically in Fig. 120. In this two relays are employed, one for current and the other for voltage and one to four contactors depending upon the number of exciters used in connection with it. Each contactor short-circuits an auxiliary rheostat in the exciter field and the coils of the contactors are connected in multiple and in turn across the exciter busbars through the contacts of the relays. Should there be a sudden rise in current flow, the cur-

rent magnet opens its contacts, or should there be an abnormal rise in voltage, the potential magnet opens its contacts, either of which operations will open the shunt across the auxiliary rheostats and reduce the voltage to a point depending upon the setting of the rheostats.

A diagrammatic illustration of the excess voltage protective device employed in connection with Westing-

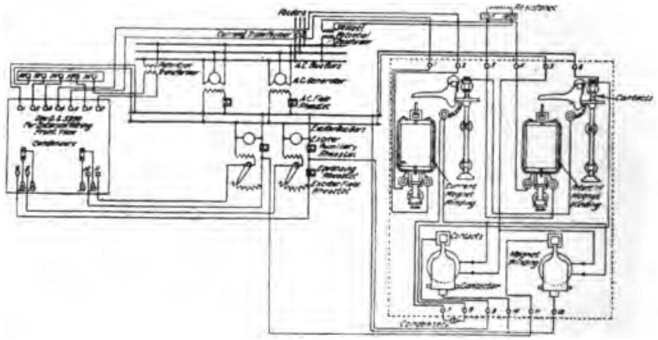


FIG. 120. CONNECTIONS OF HIGH VOLTAGE, HIGH-CURRENT CUTOUT RELAY WITH REGULATOR AND TWO EXCITERS IN PARALLEL

house alternating-current regulators is shown in Fig. 121. Essentially this device consists of a direct-current element energized from the exciter bus bars in combination with an undervoltage relay energized from the potential transformer supplying the alternating-current regulator. The relay contacts and those of the direct-current element are connected in parallel and as indicated, in series with the main contacts of the regulator.

The drop in voltage accompanying a short-circuit on the alternating-current distribution lines causes the main regulator contacts to close and the relay contacts to open. Closing of the main regulator contacts as noted in the description of the Westinghouse regulator causes all relay contacts to close, which we find by referring to Fig. 116, results in the short-circuiting of the exciter rheostat with the consequent building up of the exciter voltage. As soon as this voltage rises to the point for

which the direct-current element is adjusted, the contacts of this element begin to operate and to regulate the exciter voltage in the same manner that the main regulator contacts normally do, thus preventing the exciter voltage rising above the predetermined point. This is usually maintained a trifle above the no load excitation value required by the alternating-current gen-

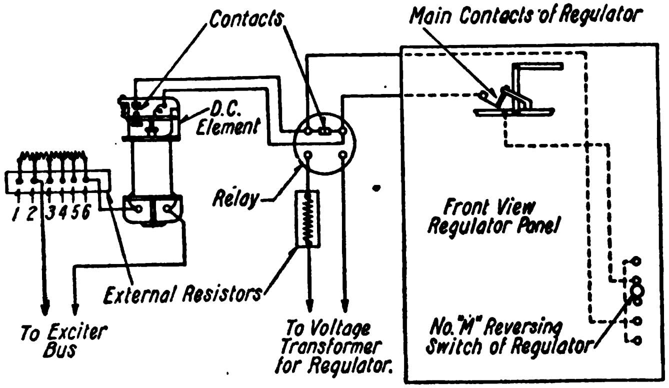


FIG. 121. DIAGRAMMATIC VIEW OF WESTINGHOUSE EXCESS VOLTAGE PROTECTIVE DEVICE

erators. As soon as the short circuit opens, the alternating-current voltage has a tendency to rise, but when it reaches a value corresponding to the setting of the undervoltage relay, the contacts of the relay close and place the regulator back into service.

Questions on Chapter XIV

1. What is regulation on an a.c. generator?
2. What is the effect of the power-factor on regulation?
3. What is the regulation where capacity reactance is greater than induction reactance?
4. How is voltage controlled by hand for an a.c. generator?
5. How should the rheostat in the exciter field be used?
6. What are the main features of the Tirrill regulator? What is the purpose of each?

7. What happens when generator bus voltage falls? When exciter voltage falls?
8. How does the relay magnet act to raise the generator bus voltage?
9. Why is regulation of voltage important?
10. What special method is used when exciter voltage is maintained constant, to regulate e.m.f. of the main generator?
11. What are the main features of the Westinghouse voltage control system?
12. What is the purpose of the vibrating magnet? Of the main magnet?
13. What causes the main contacts to close? What opens them?
14. What effect does closing the main contacts have on the relays?
15. Why is protection needed against excess voltage, when a voltage regulator is used?
16. Will the device in Fig. 118 reset itself after the high e.m.f. has been controlled?
17. Why would a short circuit on the distribution lines cause excess voltage at the generator with a voltage regulator in use?
18. In what way does the device of Fig. 121 take account of this?

CHAPTER XV

SYNCHRONIZING ALTERNATING-CURRENT GENERATORS

SYNCHRONIZER DETAILS AND THEIR ACTION

WHEN parallel operation of alternating-current generators is desired, greater precautions must be exercised than in the case of direct-current machines. Due to the very fact that the electromotive forces of such machines alternate through positive and negative values rapidly many times each second, it is necessary not only that the voltage of the incoming machine be equal to that of the bus bars but that the number of alternations per second, or frequencies, should be of like value and the machines must be "in phase"; that is, all corresponding points on the electromotive force curves of the various machines so connected, must coincide.

Phase relations may be determined by synchronizing lamps or synchronism indicators; due to their greater degree of accuracy and reliability, the latter are, however, more generally employed.

In Fig. 122 are shown two single-phase machines, A and B feeding a pair of bus bars through switches S′ and S. Connected to the machine leads are two transformers, T′ and T, the secondaries of which are connected in series with synchronizing lamps L′ and L, and switch SS. With the machines in synchronism, as they must be when operating in parallel, the direction of current flow from A and B through the primaries of transformers T′ and T respectively is indicated by the direction of the arrows. In each case this flow of primary current is from left to right; that in the secondary windings we know from the theory of the transformer is at any instant in a direction opposite to that in the primaries or, in this case, from right to left. Consequently the electromotive forces induced in the

secondary windings of these transformers oppose or neutralize each other and the lamps remain dark. It is, therefore, apparent that with the connections shown the only time to throw machines A and B in parallel is after their respective voltages are of like value and in phase and the synchronizing lamps are dark.

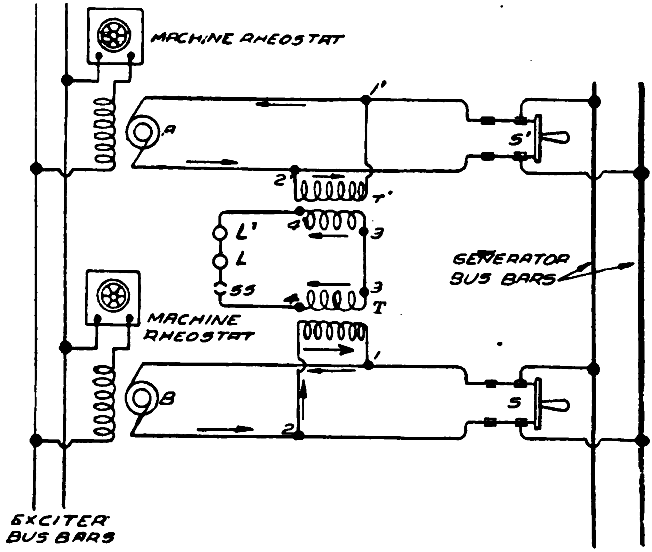


FIG. 122. DIAGRAM OF CONNECTIONS OF SYNCHRONIZING TRANSFORMERS, LAMPS AND SWITCHES AS USED WITH TWO SINGLE-PHASE GENERATORS

If, however, it is desirable to indicate complete synchronism with the lamps up to full candlepower, reverse the secondary of either transformer.

Due to the fixed relation existing between the various phases of polyphase machines, it is necessary to synchronize only one of the phases. Synchronizing equipment connections for an installation of three 3-phase machines are shown in Fig. 123.

Whether lamps shall be "light" or dark" for complete synchronism may be readily determined by means of the following procedure. In the case of a 2-machine installation, raise the brushes on one of them, throw in

the main switches and note whether the lamps are "light" or "dark." If dark, the machines are to be thrown in parallel with the lamps out; if lighted, complete synchronism is to be recognized by that condition. A similar procedure is easily arranged for machines with stationary armatures by disconnecting the proper leads.

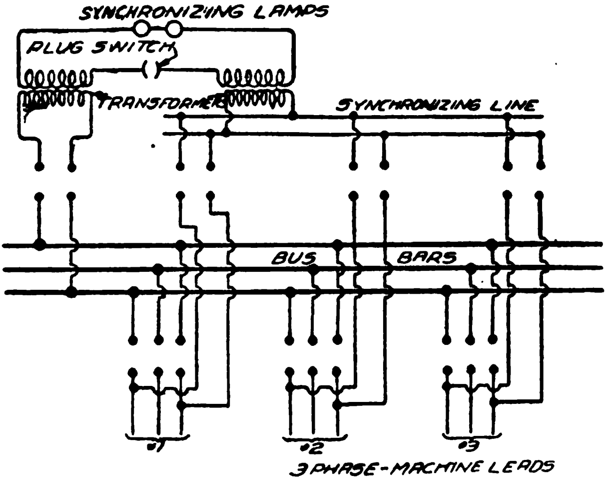


FIG. 123. SYNCHRONIZING EQUIPMENT CONNECTIONS FOR AN INSTALLATION OF THREE 3-PHASE GENERATORS

SYNCHRONISM INDICATORS

SYNCHRONISM INDICATORS or synchronoscopes are generally preferred to synchronizing lamps as they indicate more exactly the difference in phase angle at every instant and the difference in frequency between the incoming machine and that of the system to which this machine is to be connected.

In the synchronoscope, built by the Westinghouse Electric and Manufacturing Co., a rotating field is produced by current from the bus bars passing through a split-phase winding and two angularly placed coils. In this rotating field is a revolvable iron vane, or armature, magnetized by a stationary coil connected across the lines of the incoming generator. As the armature is

attracted or repelled by the rotating field of the coils connected to the bus bars, it assumes that position at which the zero of the rotating field occurs at the same instant as the zero of its own field. Thus its position

FIG. 124. WESTINGHOUSE TYPE SI SYNCHRONOSCOPE

at every instant indicates the phase angle between the voltage of the incoming machine and that of the bus bars. As this angle changes, due to difference in frequency the iron vane or armature with the attached pointer rotates, and when synchronism is reached it remains stationary.

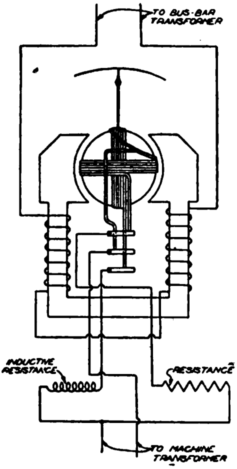


FIG. 125. CONNECTIONS OF G. E. SYNCHROSCOPE

The synchronoscope of the General Electric Co. is in construction not unlike a small 2-phase bipolar synchronous motor with the field or stator supplied with alternating instead of direct current, Figs. 125, 126. Two coils placed at angles of approximately 90 deg. and supplied with current from the incoming machines through the medium of collector rings constitute the

FIG. 126. INTERNAL VIEW GENERAL ELECTRIC SYNCHRONISM INDICATOR

armature windings; one of their coils is connected in series with a resistance while the other is connected in series with a reactance. Due to this arrangement generating a rotating field in the armature, while the stationary field is alternating, the armature tends to assume a stationary position where the fields coincide when the alternating field passes through its maximum value. Hence the armature and its attached pointer moves forward or backward at a rate corresponding to the difference of frequency, and the position when stationary, depends on the phase relation. When the machines are running at the same frequency and in phase, the pointer is stationary at the marked position.

In order to eliminate system disturbances and frequently disastrous results caused by errors in judgment on the part of operators as to the proper instant at

which to throw in the switches of the incoming machine, automatic synchronizers have been devised. These instruments automatically complete the circuit operating the closing coils of electrically-operated switches or circuit breakers when conditions are proper for synchronizing. A relay switch is interposed between the synchronism contacts and the main switch.

According to information furnished by the Westinghouse Electric & M'f'g Co., the features of the automatic synchronizer built by that company are as follows: The instrument has two solenoids, the cores of which are attached at the upper ends to either end of a lever swung centrally on a shaft. Attached to the shaft is a suitable contact arrangement which is normally open. When the machines reach the proper relation of frequency and voltage, the contact device closes and completes the circuit through the closing coil of the main switch, the current for actuating this switch being taken from a source independent of the main generators such as an exciter. Current for energizing the solenoids is derived from the bus bars and from the incoming machine through transformers. The secondary voltage of these transformers is nominally 100 v., so that the synchronizer may be placed on a control board without danger to attendants.

A control switch is used for tripping the main switch when desired, but the main switch can be closed only by the circuit through the synchronizer. A relay inserted in the closing coil circuit holds the circuit open until the proper moment for synchronizing, when the synchronizer operates the relay and completes the circuit.

Glower-Type Synchronism Indicators

While synchronism indicators of this type do not, strictly speaking, belong to the subject under discussion, their functions being practically identical to the instrument just described, mention of them will not be out of place. For synchronizing low-voltage machines or high-voltage machines in connection with which transformers are required for indicating or measuring purposes, lamps or electro magnetic indicators find their greatest field of

adaptability. But when desired to connect together systems in which transformers are not required for indicating and measuring instruments, the equipment is comparatively expensive and the higher the voltage the greater is such expense. With electrostatic synchronizers, however, no transformers are required as they operate entirely on the charging current of the line insulators.

FIG. 127. GENERAL ELECTRIC GLOWER TYPE SYNCHRONISM INDICATOR

An indicator of the type for 3-phase service is shown in Fig. 127, mounted with two 3-phase disconnecting switches on a regular switchboard panel. The synchronizer proper consists of a case containing three electrostatic glowers connected to the lines to be synchronized through the medium of the disconnecting switches and strain or suspension-type insulators. As will be noted, the terminals of one of the glowers are connected to the same phase of running and incoming lines while the terminals of the other two glowers are each connected to dissimilar phases.

With the incoming machine up to proper speed and voltage and ready to be synchronized, the disconnecting switches are thrown in at once, causing the glower elements to flicker in a manner not unlike that of the ordinary synchronizing lamps; the apparent direction of rotation indicates the relative speeds of the incoming and the running machines. When these machines are, however, in exact synchronism, the rotation will stop and

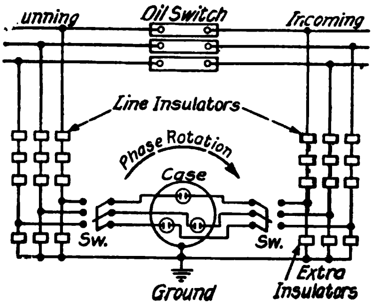


FIG. 128. DIAGRAM OF CONNECTIONS OF GENERAL ELECTRIC ELECTROSTATIC SYNCHRONISM INDICATOR

the upper glower, Fig. 128, that one, the terminals of which are connected to the same phase, will be dark, while the others will remain lighted, but at about one-half brilliancy.

QUESTIONS ON CHAPTER XV

1. When are alterating-current generators "in phase"?
2. How can this be determined practically?
3. What connections are changed to convert synchronizing lamps from "light" to "dark"?
4. How can you tell whether synchronizing lamps are connected to indicate "light" or "dark"?
5. What is the principle of the "synchronoscope"? How does it indicate synchronism?
6. How does the "synchronizer" operate?
7. What is the advantage of the glower-type of synchronoscope?

CHAPTER XVI

THE STATIC TRANSFORMER

Theory of Operation and Construction

IN ORDER to understand the workings of the static transformer, it is necessary first to have a clear conception of the theory of electromagnetic induction, for it is upon this that operation of the transformer is based. The laminated iron structure shown in Fig. 129 has wound upon two legs coils of insulated magnet wire, one of which connects through the medium of a reversing switch to a source of direct current, in this case a battery, while the other connects to a differential low-reading voltmeter; that is, a voltmeter with zero graduated at the center of the scale and reading to the right and left of this. The direction of deflection of the needle depends upon the direction of current flow through the windings of the instrument.

It is evident that with the reversing switch in the position indicated, no current can flow through the left-hand coil winding; however, upon moving the blades of this switch to the right, contact is made at points 1 and 2 and immediately a flow of current is established which, passing through the left-hand coil, energizes it and thereby creates a magnetic flux in the iron core. The establishment of this flux is not instantaneous, but comparatively gradual and as the right-hand coil lies within the influence of this increasing magnetic field, it has induced in it an electromotive force the direction and intensity of which is indicated by the connected voltmeter.

Throwing the reversing switch to the left so as to bring its blades in contact with terminals 2 and 3 causes the current to flow through the left-hand coil winding in the opposite direction. As a consequence, the magnetic flux established within the iron core is also of opposite direction as is also the direction of the electromotive

force induced in the winding of the right-hand coil, a fact quite apparent from the reversed deflection of the voltmeter pointer.

It is evident therefore that by rapid manipulation of the reversing switch an electromotive force, almost continual, although of fluctuating characteristic, may be induced in the right-hand coil. If in place of the direct battery current and the reversing switch, a source of alternating electromotive force such as an alternating-

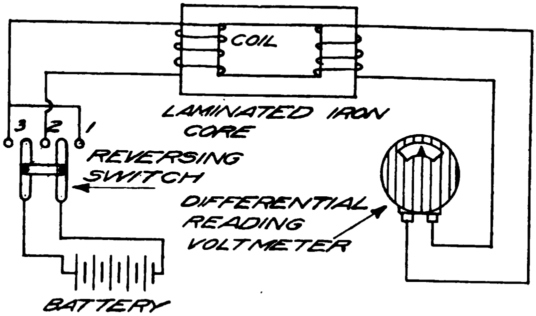


FIG. 129. ILLUSTRATING PRINCIPLE OF OPERATION OF THE STATIC TRANSFORMER

current generator be used, the characteristics of the electromotive force induced in the right-hand coil will be similar to those of the source of supply although at any instant the induced or secondary electromotive force is opposite in direction to the inducing or primary electromotive force. The transformer winding connected to the source of supply is generally termed the primary while the other, that connected to the load, is referred to as the secondary.

With the secondary circuit open and an alternating electromotive force applied to the primary winding, the magnetization of the core alternates as does the primary electromotive force, although the magnetizing action lags somewhat behind the current producing it. As a consequence, the changing magnetic flux induces within the winding a counter electromotive force which opposes the applied electromotive force, thus limiting the current

flow to an amount just sufficient to maintain magnetization of the core. This current is called the magnetizing current and may be represented by the letter M.

With the secondary circuit closed, the alternating magnetic flux sets up an e.m.f. in that circuit, consequently a current. This current is nearly opposite in phase to that in the primary winding, hence tends to set up a magnetic flux opposed to that created by primary current. This results in an increased flow of primary current I' to keep up the magnetic flux that it has started, and the rise is only limited by the resistance of the secondary circuit and of the primary winding.

The magnetizing action of the primary current I' is measured by the product of this and the number of primary turns N' or $I'N'$. Similarly, the magnetizing action of secondary current I'' is measured by $I''N''$ where N'' is the number of secondary turns. We then have $I'N'$ equal to $I''N''$ or, $I' \div I'' = N'' \div N'$ indicating the currents to be inversely proportional to the number of turns.

Due to the rapid reversals of magnetization, a certain electromotive force a is induced in each turn of the windings and as the total electromotive force induced in the primary is nearly equal and opposite to the applied electromotive E', we have $E' = aN'$ and similarly in the case of the secondary winding $E'' = aN''$. The ratio of the primary electromotive force E' to the secondary electromotive force E'' is then as the number of primary turns N' is to the number of secondary turns N''.

Let us assume having a transformer with primary winding of 1000 turns designed for 2300 v. and with secondary winding of 100 turns. What will be the secondary voltage?

We know $E' \div E'' = N' \div N''$, or $2300 \div E'' = 1000 \div 100$, or $2300 \div E'' = 10$. Transposing, we have, $E'' = 2300 \div 10$, or 230, as the secondary voltage.

A transformer of the type just discussed generally termed the constant-potential transformer. and used wherever a practically constant voltage (but variable current) is required is shown in elementary form in Fig. 130.

CONSTANT-VOLTAGE transformers may, according to structural details, be either of the shell or core types. Figure 131 illustrates a cross-sectional view of a shell type transformer. Coils C′ are surrounded on both sides

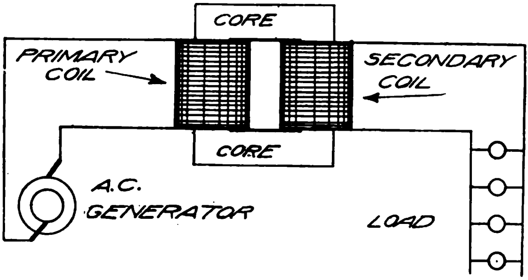


FIG. 130. A STATIC TRANSFORMER CONNECTED TO ITS SOURCE OF CURRENT AND ITS LOAD

by a built-up laminated iron core, C, provided with ventilating spaces, V, which also aid in the free circulation of cooling oil. The laminations are stamped in two parts and are built up about the assembled coils as shown, A, B and C being the divisions between the two

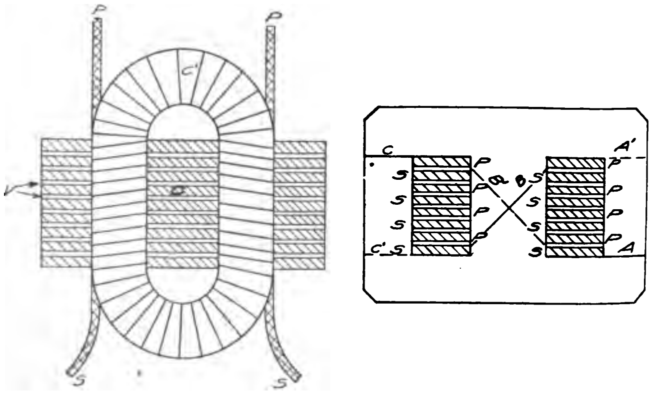


FIG. 131. CROSS-SECTIONAL VIEW OF SHELL TYPE TRANSFORMER

parts of the top sheet and A′, B′ and C′ the divisions of the sheet next to the top; P and S are the primary and secondary coils respectively.

Such materials as fibre, paper, fuller board, oiled cloth and micanite are used as insulation. After the coils are wound, they are placed in a vacuum tank where an insulating compound is injected which thoroughly impregnates the windings.

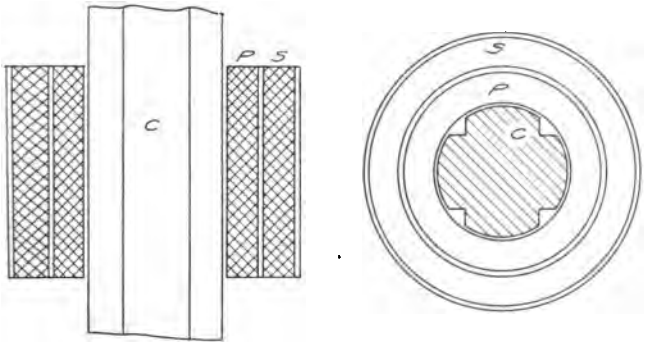


FIG. 132. CROSS-SECTIONAL END AND SIDE VIEWS OF ONE LEG OF A CORE TYPE TRANSFORMER

Cross-sectional end and side views of one leg of a core type transformer are shown in Fig. 132. P and S are primary and secondary windings respectively and C the laminated iron core made irregular in shape to facilitate the circulation of oil within the coil. The manner of insulating and treating the coils is similar to that employed in the shell type of transformer.

Polyphase

For two- and three-phase work separate single-phase transformers connected as shown in Fig. 133 may be used. This scheme is, however, not always desirable and frequently therefore so-called two- and three-phase transformers are employed; in reality these are nothing more than single-phase units mounted on special cores such as illustrated in Figs. 134 and 135. In the case of the two-phase transformer the magnetic flux in core *a*

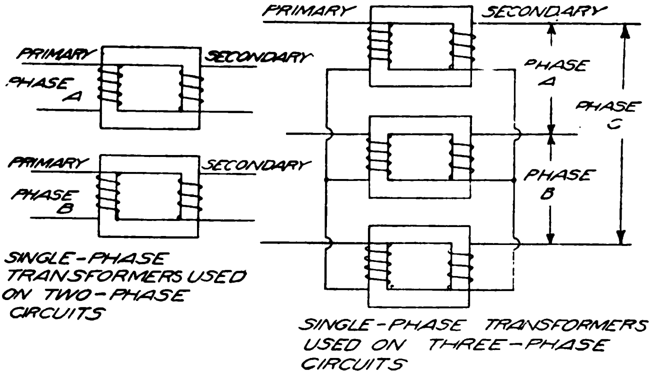


FIG. 133. SINGLE-PHASE TRANSFORMERS USED FOR TWO- AND THREE-PHASE WORK

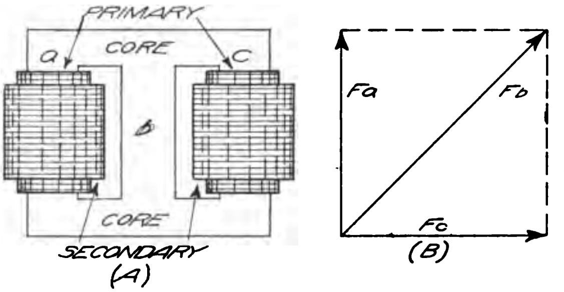


FIG. 134. TWO-PHASE TRANSFORMER AND VECTOR DIAGRAM OF MAGNETIC FLUXES

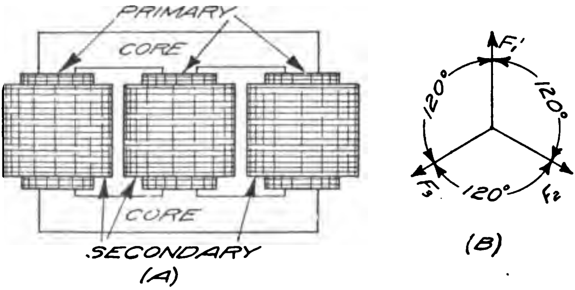


FIG. 135. THREE-PHASE TRANSFORMERS AND VECTOR DIAGRAM OF MAGNETIC FLUXES

is in quadrature to that in core *c* and that in return circuit *b* is equal to the geometric sum of *Fa* and *Fc* (as indicated at B, Fig. 134) or *Fb*. Its direction relative to *Fa* and *Fc* is as shown. Similarly the direction and value of the magnetic flux in each of the legs of the cores of the three-phase transformer is as shown in the diagram (B) Fig. 135. The magnetic flux in each of the legs is displaced by 120 deg.

Electrical Connections

Where three transformers are used on a three-phase three-wire system, the primaries may be connected to the supply mains either in delta or Y and the secondaries may likewise be connected either in delta or Y, thus

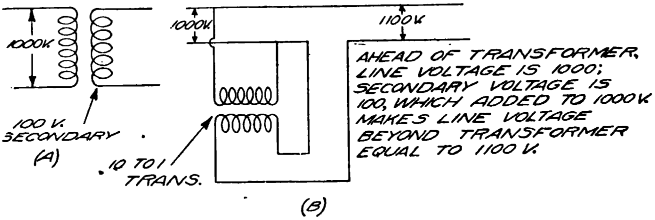


FIG. 136. ILLUSTRATING THE AUTOTRANSFORMER AND ITS APPLICATION

allowing the employment of any one of four schemes, namely: Primary delta and secondary delta; primary Y and secondary Y; primary delta and secondary Y; or, primary Y and secondary delta. The primary delta—secondary delta scheme is, however, the one usually employed, for with it any one of the single transformers may be cut out without rendering the system inoperative. Under such conditions, however, the capacity of the bank would be reduced to 0.577 of that when all three units were working together.

Auto-Transformers

The term "auto-transformers" refers more properly to the scheme of connections employed than to any particular type or form of piece of apparatus.

In Fig. 136 at A is shown an elementary diagram of connections of a single-phase transformer designed to

step down from 1000 to 100 v. Frequently it is desirable or necessary to raise the voltage of a distribution system at some given point and in order to avoid the necessity of installing otherwise expensive voltage boosting apparatus such a transformer may be used instead. Its application is shown at B, Fig. 136, and from this it is evident that with the primary of the transformer connected across the line and its secondary in series with the line (beyond primary connections) the line voltage due to the added 100 v. will be 1100 v. This may more properly be called a boosting transformer although by reversing the secondary connections it is possible to cause the secondary 100 v. to oppose the primary 1000 v., in which event, of course, the transformer would rather be called a "bucking" transformer. If so employed, the primary line voltage would be reduced to 900 v.

The advantage of using such a scheme lies in the fact that a comparatively small transformer may serve a purpose that would otherwise require a much larger unit. With a current of 500 amp. delivered to the receiving circuit at a voltage of 1100 v., the total power would be equal to 550 kv.a , the required capacity of a transformer if used in a regular way. By the use of an auto-transformer, however, and where the secondary voltage is 100, the capacity required is equal to but 500 times 100, or 50 kv.a.

Questions on Chapter XVI

1. What is the effect of a reversal of current in a coil surrounding an iron core?
2. What is the phase relation of the secondary e.m.f. to the primary e.m.f.?
3. What limits primary current when the secondary circuit is open?
4. How does closing the secondary allow more primary current to flow?
5. What limits the secondary current?
6. What determines the ratio of primary e.m.f. to secondary? Of primary current to secondary?
7. A transformer has 6600 volts from the generator.

The primary has 500 turns and the secondary 2500. What will be the line voltage? (33,000 v.)

8. If the generator of question 7 is delivering 100 amp. what will the line current be? (20 amp.)
9. What is the shell type of transformer? The core type?
10. Which will have greater magnetic leakage?
11. What four methods of connection may be made for 3-phase transformers?
12. What advantage has the delta-delta system?
13. What is an auto-transformer? For what is it used?
14. To boost the e.m.f. of a 2200-v. line to 2400 v. when carrying 250 amp what capacity booster would be needed? (50 kv.a.)

CHAPTER XVII

TRANSFORMER CONNECTIONS

CONSTANT-CURRENT TRANSFORMERS; PHASE TRANSFORMATIONS AND METHODS OF CONNECTION FOR VARIOUS PURPOSES

REGULATION of transformers, similar to that of generators, is equal to the difference between full load and no load secondary voltage expressed as a per cent of full-load secondary voltage. Thus, a given transformer connected to a constant-voltage primary line has a full-load voltage of 109 and a no-load voltage of 112; its regulation is then equal to the quotient obtained by dividing the difference between 109 and 112, or 3, by 109. This is equal to 0.027, or 2.7 per cent, the regulation of the transformer.

Resistance of the coil windings and magnetic leakage are the two factors responsible for the change in secondary voltage with change of load. With a non-inductive load, voltage change is due almost entirely to coil resistance, while, where the transformer is supplying current to a highly inductive load, decrease in secondary voltage is due to magnetic leakage, which also causes an increase in terminal voltage with increase of load where the secondary of a transformer feeds a circuit of high capacity.

Dividing the output of a transformer by its input (both in watts) will give the efficiency. At light loads, as in the case of any machine, the efficiency of the transformer is comparatively low; above 25 per cent of its rated capacity, however, the efficiency is high, in many instances for large size units operating at full load exceeding 99 per cent. A typical transformer efficiency curve is shown in Fig. 137.

ALL-DAY EFFICIENCY

TRANSFORMERS primarily employed to furnish light and power are ordinarily termed distribution trans-

formers, and, due to the fact that they supply energy but a comparatively short time during each 24 hr., their all-day efficiency is as a rule quite low. Let us assume that a 15-kv.a. transformer having an iron or core loss of 500 w. and a copper loss of 500 w. when fully loaded, works at full capacity (and unity power factor) but 2 hr. each day and is without load the remaining 22 hr.

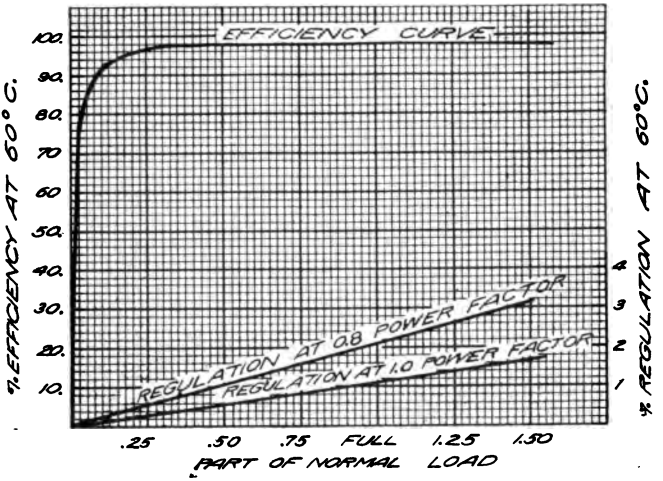


FIG. 137. TYPICAL TRANSFORMER EFFICIENCY AND REGULATION CURVE

The core loss remains constant, so that this for 24 hr. amounts to 24 times 500, or 12,000 w.-hr., while the copper loss is equal to 2 times 500, or 1000 w.-hr. When the transformer is working at rated capacity, that is, is delivering 15,000 w., it is being supplied with 500 + 500 + 15,000, or 16,000 w. per hr. or 32,000 w.-hr. for the 2 hr. of full load working. It is, however, receiving, during the remaining 22 hr., 22 times 500 w., or 11,000 w.-hr. to compensate for the continuous core loss. The total energy delivered to the transformer during the day is then equal to 32,000 plus 11,000 w.-hr., or 43,000 w.-hr., the total output 30,000 w.-hr., so that the all-day efficiency is equal to 30,000 divided by 43,000 equals 0.698, or 69.8 per cent.

Let us again assume that this transformer, instead of being operated but 2 hr., is made to supply full rated capacity for 10 hr., and make a comparison of the efficiency. The core or iron loss remains at 24 times 500, or 12,000 w.-hr., the copper loss is equal to 10 × 500 or 5000 w.-hr. and the output 150,000 w.-hr., thus making a total of 12,000 plus 5000 plus 150,000 w.-hr., or 167,000 w.-hr. of energy delivered to the transformer. Its output is 150,000 w.-hr., which, divided by 167,000, is equal to 0.898, or an all-day efficiency of 89.8 per cent.

Cooling Systems

Unless means be provided for removing it, the heat developed within the cores and windings of transformers will be destructive to the insulation. Various schemes are employed for this purpose, among which are the following:

(1) Natural circulation of air and radiation.

(2) Forced circulation of air.

(3) Natural circulation and radiation with two fluids.

(4) Combination of natural circulation of a fluid medium with forced circulation of cooling air.

(5) Natural circulation of an insulating fluid cooled artificially by another fluid.

(6) Forced circulation of an insulating fluid cooled in any convenient way.

For small distributing transformers, that is, for units up to 25 kv.a. rated capacity, and for instrument and switchboard transformers the first-mentioned scheme is the one most generally employed, while the forced convection of air method, or, in other words, the air-blast method, is the one utilized on transformers having rated capacities up to 5000 kv.a. and operating at voltages less than 35,000 v. It is common practice to use about 150 cu. ft. of air per minute per kilowatt of loss, the air being forced through the transformer by a blower at a pressure of from 0.5 to 1.5 oz. per square inch.

In the third method, applicable to transformers with rated capacities up to 4500 kv.a., the windings are cooled both by natural convection of air and oil circulating

around and between the coils and the cores. The combination of natural convection of a fluid medium with forced circulation of cooling air is a scheme not used extensively in this country, and therefore not calling for discussion. The other two arrangements consist of insulating the windings with oil and cooling by forced circulation of water and by forced circulation of the cooling medium.

FIG. 138. TRANSFORMER OF THE CONSTANT-CURRENT TYPE

The required physical characteristics of a cooling fluid may be enumerated as follows: It must be a good insulator and must possess good thermal conductivity and high specific heat. Its co-efficient of expansion should be high and its viscosity as low as possible.

CONSTANT-CURRENT TRANSFORMERS

THESE are used primarily in connection with series street lighting systems or wherever a constant secondary current at variable voltage is desired. An elementary form of such a transformer is shown in Fig. 138. It

consists of a laminated iron structure or framework carrying one or more stationary coils, the primaries, and one or more movable secondary coils, which, as shown, are nearly balanced against gravity by a counterweight connected to the coil by a strap or cable passing over a sheave. A dashpot is provided to prevent sudden oscillations of the coil.

With constant load, that is, with fixed secondary external circuit resistance, the movable coil assumes a given position. But, should the resistance of the external circuit be decreased, greater flow of current will result,

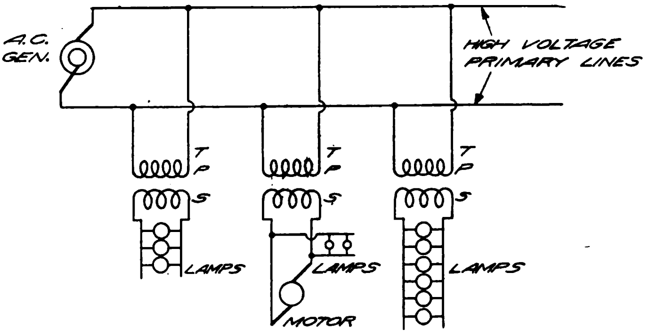


FIG. 139. METHOD OF CONNECTING SINGLE-PHASE TRANSFORMERS

which causes an increase of repulsion between the two coils, and, as a consequence, the upper coil moves upward and the increase of leakage of flux lessens the useful flux through the secondary coil. This reduces the induced voltage in the secondary coil, thus counteracting the tendency of the current to increase. If the external circuit resistance increases, the opposite action takes place. The flow of current is cut down, with the result that, due to the decreased repulsion between the two coils, the upper coil moves downward. The leakage of flux is thereby decreased, the useful flux increased and more current caused to flow through the external circuit.

Frequently the primary coil is made movable and the secondary coil fixed. Sometimes both coils are made movable, in which case they may be made to counter-

balance one another by the employment of suitable mechanism and counterweights.

Where the capacity of the transformer does not exceed 100 kv.a., air cooling is used; but, where the capacity exceeds this figure, the transformer is immersed in oil, and, in some instances, water cooled.

Connections

In a single-phase constant-voltage system, the individual transformers are connected in parallel across the

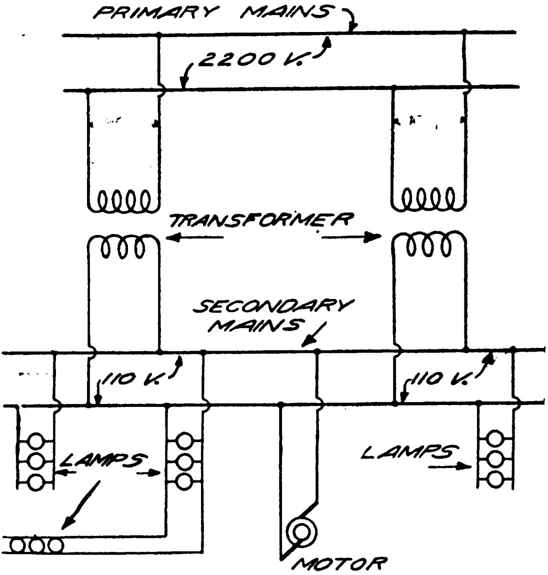


FIG. 140. DIAGRAM OF CONNECTION OF "BANKED" TRANSFORMERS

two main lines, in the manner indicated in Fig. 139. Current is supplied by the alternating-current generator at high voltage to the primaries P of the transformers T, which step down the voltage to a value dependent upon the ratio of primary to secondary winding turns; secondary windings S then deliver the current at the reduced voltage to the consuming devices, which may be in the form of lamps, motors, etc. Frequently, and especially

in districts where a heavy demand for current exists, not only the primary windings are connected in parallel, but also the secondary windings. This scheme of connections, often termed "banking," is illustrated in Fig. 140, and, when employed, care must be exercised to see that the ratio of primary turns to secondary turns is the same in each unit and that the voltage drop from no load to full load is the same, both in magnitude and

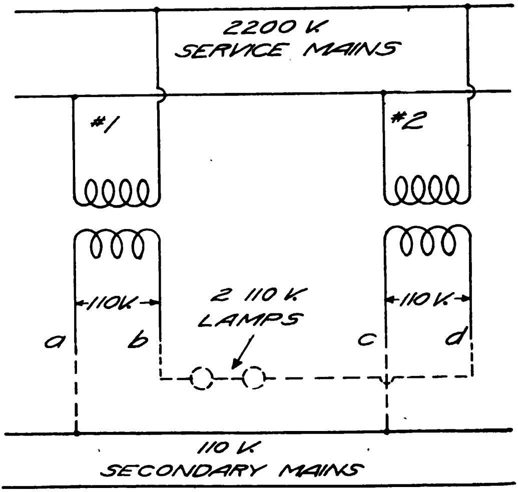


FIG. 141. CONNECTIONS FOR TRANSFORMER POLARITY TEST

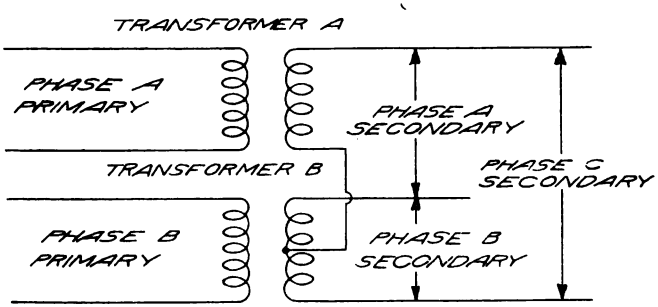
in phase, for all of the transformers so connected. With unequal ratios of transformation, the secondary voltages will be unequal, and, as a result, the unit or units having the higher secondary voltages will carry the heavier loads.

Before connecting two or more transformers in parallel, it is advisable first to conduct a polarity test. To do this, refer to Fig. 141, showing two single-phase transformers with primaries connected in parallel across the service mains and with secondaries of the two units, Nos. 1 and 2, lettered a, b, c and d. Connect secondary leads a and c to either one of the secondary mains, and, between terminals b and d connect two 110-v. lamps

(lamps of such voltage rating used when secondary voltage of each transformer is 110-v.). If the lamps do not light, terminals a and c are to remain as connected, and b and d made to tie in with the other secondary main; but, should the lamps light, secondary leads a and d must be connected to one secondary main and b and c to the other.

Two- to Three-Phase Transformations

Prior to the general use of three-phase alternating-current generators, but while two-phase machines were



Secondary turns on transformer B $= 2 \div \sqrt{3}$ times secondary turns on transformer A.

FIG. 142. SCOTT SCHEME OF CONNECTION FOR TWO-PHASE TO THREE-PHASE TRANSFORMATION

being generally introduced, the economy of three-phase transmission was appreciated, and, while many of the systems constructed were designed for two-phase work, they could not, without the use of expensive machinery, be then used for the handling of three-phase currents. Scott, however, devised a scheme of transformer connections whereby the current supplied by a two-phase machine could readily be transformed to three-phase, and, as a consequence, even today many of the early two-phase generators are used to serve three-phase systems, frequently being operated in parallel with three-phase machines.

In the Scott transformer, as shown by the diagram of connections of Fig. 142, two similar primary coils are connected to the two-phase supply mains, while one leg of the secondary winding of one of the transformers ties in with a tap brought out from the mid point of the secondary coil of the other transformer. In order, however, to provide a like voltage across any two of the secondary mains, the number of turns of wire on the secondary winding of transformer A must be equal to $\sqrt{3}$ times the number of turns on each half of the secondary of the other transformer or the number of secondary turns on unit A is equal to $\frac{1}{2}\sqrt{3}$ times the total number of secondary turns on transformer B.

Questions on Chapter XVII

1. If your average load was 100 kv.a. and you had a 500 kv.a. transformer, would it be wise to use that transformer? Why?
2. What is the all-day efficiency of a transformer?
3. What determines the secondary e.m.f. of a transformer?
4. How will increasing the core area affect the voltage? The core loss?
5. If you cut down core area, how could you keep up the total flux?
6. How could core loss of a transformer be lessened when designing it?
7. For a transformer having core loss of 200 w., copper loss 150 w.. rating 6000 kv.a. and full load period 2 hr., what is the full load efficiency? The all-day efficiency? (94.6%; 70.3%.)
8. If the transformer of question 7 had been designed for core loss 150 w. and copper loss 200 w., what would be the full load efficiency? The all-day efficiency? (94.6%; 79.8%.)
9. What would be the all-day efficiency of question 7 if the full load period was 8 hr.? (94.1%.)
10. What would be the all-day efficiency of question 8 if full load period was 8 hr.? (90.2%.)
11. For short peak load which transformer would be better? For long steady load?

12. What are the common methods used for cooling transformers?
13. How does the constant-current transformer act to deliver steady current from a constant voltage line?
14. What is the object of the Scott connection for transformers? How is the connection made?
15. If transformer B, Fig. 142, has 100 turns on the secondary, how many turns should A have? (87 turns.)
16. If secondary voltage of B is 110, and primary voltage is 6600, how many turns would there be in the primary coil? (6000.)
17. With primary coil the same as for B, what would be the secondary voltage of transformer A? (96 v.)
18. What is meant by "banking transformers"?
19. What precaution must be taken in selecting transformers for banking?
20. What is the method of testing for polarity?

CHAPTER XVIII

FEEDER VOLTAGE REGULATORS

THEORY OF OPERATION; CONSTRUCTION; OPERATION; LOSSES

ENGINEERS operating plants supplying service to restricted territories where the length of transmis- and distribution lines is comparatively short, are not confronted with the difficulty of being unable to maintain an approximately equal voltage on all circuits. This is a condition, however, which bothers the man responsible for the operation of the plant supplying energy to alternating-current circuits of great lengths and carrying unequal loads.

This condition exists in stations having 3-phase generators supplying single-phase circuits; and to overcome this difficulty voltage regulators are employed.

THEORY OF VOLTAGE REGULATORS

SINGLE-PHASE voltage (or feeder) regulators are autotransformers with their primary coils connected across the bus bars and their secondary coils in series with the feeder circuit. They are of 3 general types as follows: (a) A type in which the secondary coil has many leads brought out to points on a dial switch, so that the number of active turns on the secondary coil may be changed at will, permitting of the adjustment of the feeder voltage to any desired value.

(b) A type in which the primary and secondary coils are wound at right angles to each other on the inner face of a laminated iron ring, not unlike the stator of an induction motor. The magnetic flux, due to the primary coil, is made to pass in whole or in part through the secondary coil by turning a laminated core.

(c) Polyphase feeder regulators usually consist of several single-phase regulators, one for each phase. The advantage of this arrangement is that the voltage of each phase may be controlled separately. A combined polyphase feeder regulator is, however, sometimes used.

Figure 143 is a diagram of connections of the type of regulator outlined in (a). As may be seen, the primary coil is permanently connected across the bus bars. One feeder wire passes out directly from the buses and

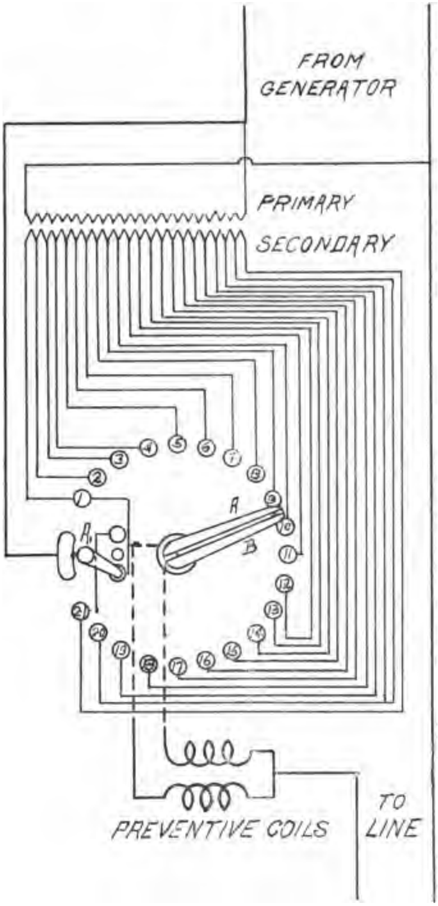


FIG. 143. INTERNAL CONNECTIONS OF TYPE (A) REGULATOR

the other passes through few (or many) turns of the secondary coil and then to the line. The reversing switch, A_1, serves to connect the feeder to one or the other terminal of the secondary coil, and the arm of the dial switch connects the line wire to any one of the

taps which are brought out from the secondary coil. For one position of the reversing switch, the induced voltage in the secondary turns which are connected in series with the feeder circuit, is added to the generator voltage, thus raising the feeder voltage. For the other position of the reversing switch, the induced voltage in the secondary turns, which are in series with the feeder circuit, is opposed to the generator voltage, thus reducing the feeder voltage.

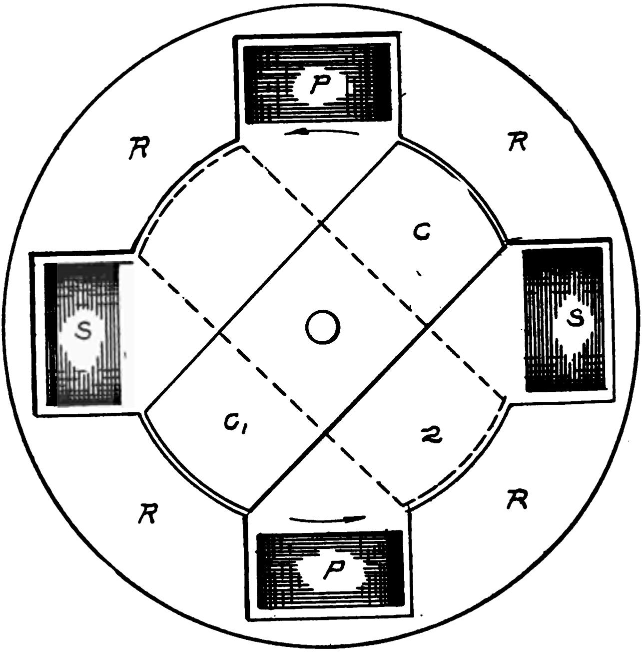


FIG. 144. DIAGRAM OF MAGNETIC VOLTAGE REGULATOR

When the arm of the dial switch touches two adjacent contact points (and it must always be arranged to touch one point before it leaves the other) the intervening turn (or turns) of the secondary coil of the regulator is short-circuited. To overcome this difficulty, the arm is made double, that is, of leaves A and B. These arms are shown connected to two contact points, say 8 and 9, and connect to a special form of choke coil consisting of two windings on one iron core. These two windings

are arranged so that equal currents flowing out from A and B circulate around the core in opposite directions so that the core is not magnetized and the windings have no choking action, except that when the two fingers, A and B, touch adjacent points of the dial switch, the turns of wire in the regulator secondary coil tend to send a large current out on A, for example, and back on B. This current circulating around the core in the same direction magnetizes the core, and the windings, in consequence, have a considerable choking action, the effect being to choke currents flowing oppositely in the fingers A and B, and to allow currents in the same direction to flow freely through them.

Under (b) is found a type of regulator sometimes called the magnetic voltage regulator. As shown in Fig. 144, a laminated iron ring, R R R R, has four large, deep slots on its inner face in which the primary coil P P and the secondary coil S S are placed. A laminated core, C C, mounted on a spindle is arranged to be turned into any desired position by means of a hand wheel or, as is now usually done, by a small electric motor. In the position indicated by full lines, the core carries the magnetic flux due to the primary coil in one direction through the secondary coil, and in the position indicated by the dotted lines, the core carries the magnetic flux due to the primary coil in the other direction through the secondary coil. When the core is moved slowly from position 1 to position 2 in the direction indicated by the arrows, the voltage induced by the secondary coil changes gradually from a full positive value to a full negative value in its relation to the primary voltage. That is, when the core is in position 1, the induced voltage in the secondary coil has its greatest value of, say, 100 v., which, if the coils are properly connected, is added to the bus bar voltage, E, giving a feeder voltage of E + 100. When the core is midway between 1 and 2, the induced voltage in the secondary coil is zero and the feeder voltage is then equal to the bus bar voltage, E. When the core is in position 2, the induced voltage in the secondary coil is again at maximum of, say, 100 v., but in such a direction as to oppose the bus bar voltage so that the feeder voltage is equal to E — 100 v.

A valuable feature of the magnetic type of regulator is that it produces a continuous variation of voltage, while type (a) produces a step-by-step variation.

The third or induction type of regulator is so called from its similarity to the induction motor. Action of the

FIG. 145. TYPICAL 3-PHASE MAGNETIC REGULATOR WITH MOTOR CONTROL

induction regulator in simplest terms is as follows: A regular induction motor stator has its windings connected across the polyphase bus bars. The magnetic field thus produced rotates in synchronism with the generator or generators which are supplying current to the bus bars. Inside of this stator (or primary) is placed an induction motor armature which does not revolve, but it is mounted

on a spindle so that it may be turned through an angle of 60 or 90 deg., either by means of a hand wheel or an electric motor. The rotating stator magnetism induces polyphase electromotive forces in the windings of this polyphase armature, which are in synchronism with the electromotive forces between the bus bars. The two (or more) windings of the polyphase armature are connected in series with the two (or more) feeder circuits (constituting of course one set of polyphase feeders) which are to be regulated. The electromotive forces in the stationary armature windings may be in phase with the bus bar electromotive force, in which case the regulator raises the voltage by the greatest amount of which it is capable. By turning the stationary armature by means of the hand wheel (or motor) and worm gear, the phase difference between the bus-bar voltages and the voltages induced in the stationary armature windings may be gradually changed from coincidence of phase to opposition of phase, during which time the boosting effect of the regulator will gradually drop to zero, become negative, and reach its greatest negative value when opposition of phase is reached. Thus, if the electromotive force induced in each armature winding of the regulator is 100 v., and if the bus bar voltage (each phase) is 1000, then the voltage between the feeders can be varied from 900 to 1100 v., by means of the regulator.

Ratings of Regulators

The amount of power delivered to service mains at a slightly increased voltage produced by an auto-transformer is much greater than the power actually transformed from the primary to the secondary of the transformer. In fact, the power actually transformed is equal to the increase (or decrease) of voltage multiplied by the total current delivered, and the rating of the auto transformer (which determines its size) is based upon the power transformed.

For example, a voltage regulator is to be used for raising the voltage of 2000-v. bus bars to a maximum of 2100 v. and the maximum current to be handled is 100 amp. In this case, the transformer rating of the reg-

ulator is 100 amp. at 100 v. or 10 kw., whereas the total power to be delivered to the feeders is, at its maximum, 2100 v. × 100 amp. or 210 kw.

Since a voltage regulator transforms but a small fraction of the power delivered to the feeders which it controls, the losses of power in the regulator are small. Thus the 10-kw. regulator may have a total loss of 300 w., which is 3 per cent of the power transformed by the regulator and only 1/7 of 1 per cent of the total power delivered to the feeders.

Questions on Chapter XVIII

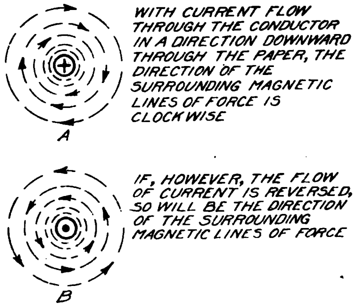
1. Why are voltage regulators needed on feeders? Why not vary the generator voltage?
2. How are the coils of voltage regulators connected?
3. What three types of regulator are commonly used?
4. Why are the connections of the primary coil in Fig. 143 reversed?
5. What determines the voltage which the secondary coil must be designed to deliver?
6. Why are the preventive coils used in the switch arm circuit?
7. In Fig. 144, what would be the effect when the core stands directly opposite the coil S S?
8. What effect would increasing the size of the core have on the change in voltage?
9. What advantage has the magnetic type regulator over the dial type?
10. Show graphically what effect an induction regulator giving 150 v. from the armature winding would have on a 1000 v. bus bar voltage when the phase difference is 45 deg. boosting. When it is 90 deg. When it is 45 deg. bucking. What would the feeder voltages be? (1120; 1020; 890.)
11. For question 10, what would be the kv.a. rating if current to be carried was 200 amp.? (30 kv.a.)
12. What would be the kv.a. rating of the circuit at maximum voltage? (230 kv.a.)
13. If the loss in the regulator is 5 per cent of its rating, what per cent will it be of total maximum power of the feeder? (0.652 per cent.)

CHAPTER XIX

THE DIRECT-CURRENT MOTOR

THEORY OF OPERATION AND CHARACTERISTICS

ELECTRIC motors are employed for the conversion of electrical energy into mechanical energy and, as in the case of the generator, electromagnetic induction is utilized, although, as the function of the machine is reversed, so is the process of conversion reversed. Briefly stated, the functioning of an electric motor is due to the reaction of (1) the magnetic field surrounding a set of conductors carrying an electric



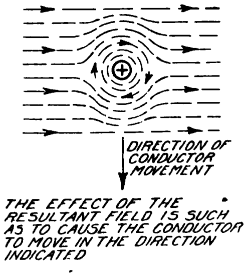


FIG. 146. RELATION BETWEEN CURRENT FLOW THROUGH A CONDUCTOR AND DIRECTION OF RESULTING MAGNETIC LINES OF FORCE

FIG. 147. EFFECT OF CURRENT-CARRYING CONDUCTORS WITHIN A MAGNETIC FIELD

current and mounted on an armature and (2) the magnetic field in which the armature carrying these conductors is placed.

A and B, Fig. 146, show sections of electric conductors, the former carrying current in a direction down through the plane of the paper, while that at B carries current in a direction up through the plane of the paper.

Direction of the magnetic lines of force created by the current flow and surrounding these conductors is then as shown, those in the case of the conductor, A, being in a clockwise direction and those for B being counter-clockwise.

As shown in Fig. 146, the magnetic lines of force encircling a conductor carrying an electric current are concentric, the intensity decreasing as the distance from the conductor increases. If, however, a conductor carrying an electric current is placed within a magnetic field,

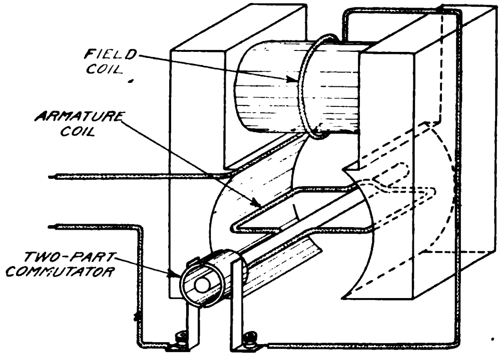


FIG. 148. THE ELEMENTARY DIRECT-CURRENT MOTOR

as indicated in an elementary manner in Fig. 147, it is apparent that, on the side of the conductor where the direction of the magnetic lines of force of the magnet is the same as those, due to the current flowing through this conductor, the intensity of the magnetic field is increased while on the other side because of the opposing lines of force, the field is weakened. As a result, the conductor is forced in the direction indicated, that is, from the portion of the field of greater intensity to that of lesser intensity. This is the principle underlying the operation of the electric motor.

Figure 148 illustrates a simple two-pole motor equipped with but a single field coil and a single-coil armature fitted with a two-part commutator; a longitudinal section through this machine is shown in Fig.

149. With the armature coil in the position indicated, direction of current flow is from the left-hand segment along the left half of the coil (that is, in Fig. 149, downward through the plane of the paper) through the back connection and thence along the right half to the connecting segment. Under these conditions and assuming the left pole face to be "north," the magnetic field above the left inductor is of greater intensity than that below and similarly in the case of the right inductor the intensity of the magnetic field below is greater than above. That, as a consequence, the coil will tend to revolve in the direction indicated by the arrow, is obvious.

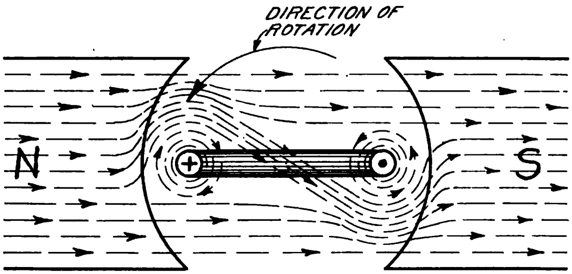


FIG. 149. LONGITUDINAL SECTION THROUGH MOTOR SHOWN IN FIG. 148

When, however, the coil moves sufficiently far to bring its plane perpendicular to the magnetic lines of force of the field, the current flow through the coil is reversed, by means of the commutator provided for the purpose. It is thus evident that rotation will continue in the same direction, for, while the direction of current flow through the armature coil has been reversed, the relative directions of field magnetic flux and conductor magnetic flux remain unchanged.

Induced Electromotive Force

As in the generator, the armature conductors of a motor cut the magnetic lines of force comprising the field flux and, therefore, have induced within them an electromotive force dependent in value upon the total

number of magnetic lines of force in the field, the number of conductors in series and the number of revolutions made per minute by the conductors.

In the study of the generator, Chapter I, it was explained how, when an electric conductor moves across a magnetic field at such a rate as to cut 100,000,000 lines of force per second, it will have induced within it an electromotive force of 1 v. Similarly, if two conductors connected in series are caused to cut 200,000,000 magnetic lines of force each per second, or if four conductors connected in series cut 100,000,000 magnetic lines of force each per second, the induced electromotive force will in each case be equal to 4 v.

With E representing the average number of volts induced, F the total number of lines of force cut, Z the number of conductors in series and the N the number of revolutions made per minute by each conductor, the value of E may be determined by the following formula:

$N = \frac{E}{Ft}$

$$E = F\,Z\,N \div (100{,}000{,}000 \times 60)$$

Such an electromotive force, because of the fact that it opposes the applied electromotive force, is commonly termed "counter electromotice force." The value of the required applied electromotive force is equal to the sum of this and the drop in the armature winding, or

$$E' = E + Ia\,Ra$$

where E′ is the applied electromotive force, E is the counter electromotive force, Ia is the armature current and Ra the resistance of the armature winding.

Transposing the foregoing counter electromotive force formula, we have the following fundamental speed equation of the direct-current motor:

$$N = [E(100{,}000{,}000 \times 60)] \div F\,Z$$

Automatic Adjustment of Current Flow

From the formula $E' = E + Ia\,Ra$, we can, by transposition, readily determine the value of the current, Ia, or the value of the counter electromotive force E, this, of course, under the assumption that the value of each of the other factors is known. The armature current $Ia = (E' - E) \div Ra$, and the counter electromotive force $E = E' - Ia\,Ra$.

In a given machine, the resistance of the armature winding, Ra, is fixed so that with constant applied electromotive force, the speed, and consequently the counter electromotive force and the current flowing through the armature will remain constant as long as the load is constant. Should, however, the load be increased, the motor armature will tend to slow down and, as a result, the counter electromotive force E is reduced. But from the foregoing formula we know that $E' = E + Ia\,Ra$, and with E′ and Ra fixed, this condition can hold good only by an increase of Ia, the armature current. It is in this way that a motor is made to draw an increased amount of current with increased load.

With a reduction of load, the opposite occurs. The speed of the motor will tend to increase, thus raising the value of the counter electromotive force E and making $E + Ia\,Ra$ greater in value than E′. If stable operation is to maintain, this cannot remain so and, since E′ and Ra are fixed, the armature current(due to the increased value of the counter electromotive force E) is reduced so as again to make $E' = E + Ia\,Ra$.

Let us assume, for example, that the electromotive force applied to the terminals of a motor is 110, that the resistance of the armature winding is 2 ohms and that it is desired to determine the increase of armature current due to a decrease of counter electromotive force from 100 to 90 v. as a result of a reduction of speed brought about by added load. The value of the armature current Ia is, as shown above, equal to $(E' - E) \div Ra$, or, in this particular case, $(110 - 100) \div 2$, which, we find, is 5 amp. Increase of load has, however, resulted in a drop of counter electromotive force to 90 v., so that now we have the value of Ia equal to $(110 - 90) \div 2$, or 10 amp. Thus it is seen that, with a reduction in counter electromotive force of but 10 per cent, the armature current is increased 100 per cent.

Motor Torque

Torque in a motor, that is, its turning moment, is due to the action of the field upon the armature conductors and is therefore proportional to the product of

F, the total flux, and Ia, the armature current. Torque, which is generally expressed in pounds-feet, may be determined by measuring the pounds pull of the motor belt and multiplying this by the radius of the pulley in feet. Thus, with a 2-ft. pulley and a belt pull of 150 lb., the torque would be 1×150, or 150 lb.-ft.; likewise in the case of a pulley having a radius of $1\frac{1}{2}$ ft. and a belt pull of 100 lb, the torque would also be 150 lb.-ft.

Types of Motors

According to winding connections, there are three distinct types of direct-current motors, namely: series,

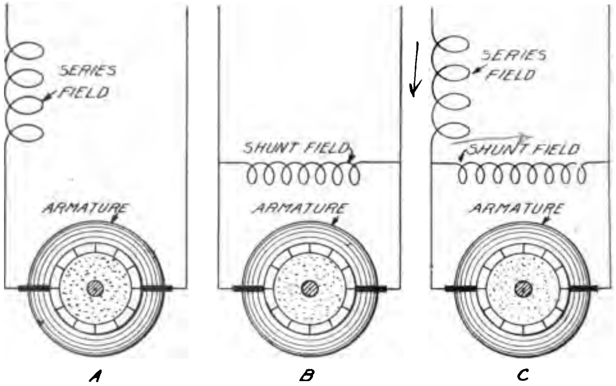


FIG. 150. ELEMENTARY DIAGRAMS OF CONNECTIONS OF SERIES, SHUNT AND COMPOUND WOUND MOTORS

shunt and compound. These are shown in diagrammatic form in Fig. 150, at A, B and C, respectively.

Except while being started and when under variable speed control, both armature and field windings of the shunt motor are connected directly across the supply mains which ordinarily should be maintained at a constant difference of potential. It is thus evident from the fundamental equation of the direct-current motor that with constant supply line voltage and as long as the load is constant, the speed of the machine will remain unchanged. With no load, the counter electro-

motive force is nearly equal to the applied electromotive force; the voltage drop across the armature windings, that is, the Ia Ra drop, is small, as is also the armature current, Ia. As soon, however, as load is thrown onto the motor, it is necessary to bring about a sufficient drop in counter electromotive force to allow that current flow through the armature windings which will provide the required torque. As already shown, the drop in electromotive force is partially due to a slight drop in speed; but, because of the increased flow of current through the armature windings, armature reaction increases and, as a consequence, aids materially in the reduction of counter electromotive force. Thus it is obvious that but a slight drop in speed accompanies increase of load on a shunt motor and it is for this reason that this type of machine is ordinarily referred to as a constant-speed motor.

Other factors affecting the speed of such a machine are the position of the brushes and the heating of the windings. With the brushes in a neutral plane, the counter electromotive force induced is a maximum and the speed at a minimum value. Shifting of the brushes, however, as in the case of the generator, renders a portion of the armature conductors inactive in the induction of counter electromotive force with the result that the flow of armature current is increased as is also the torque and consequently the speed.

Heating of the windings results in increased resistance, reduced field strength and a rise in speed. This action is, however, more than offset by the armature voltage drop with increase of load, which, as already stated, produces a slight drop in speed.

Shunt motors are but little susceptible to speed drop due to line voltage drop, the per cent of speed change being considerably less than that of voltage change. Actually the former is from 0.6 to 0.8 of the latter, so that with a 10 per cent drop in line voltage a drop in speed of but from 6 to 8 per cent may be expected.

Speed Regulation

While, theoretically, the shunt-wound motor is a constant-speed machine, practically this is not so. Drop

in speed is bound to occur with increase in load, and vice versa. Change in speed from full load to no load, expressed as a percentage of full-load speed, is called the speed regulation of the motor, voltage of supply and resistance of armature and field windings being maintained constant.

Speed Control of Shunt Motors

Speed control of shunt-wound motors may be accomplished by any one of five means:

(1) Armature current control.
(2) Field excitation control.
(3) Reluctance of magnetic circuit control.
(4) Multivoltage control.
(5) Variation of voltage.

By the first-mentioned method, a variable resistance is inserted in the armature circuit, but, due to resulting poor regulation, the large and expensive rheostat required and the inefficiency due to its use, this scheme is not extensively employed.

Although the range of speeds obtainable by varying the degree of field excitation is quite limited (generally not in excess of 30 per cent), the efficiency of a system employing this arrangement may be kept quite high. A variable resistance rheostat is connected in series with the field winding and, as more of this resistance is cut into circuit, less current flows through the field windings, the field flux is decreased, as is also the counter electromotive force. As a result, the armature current, the torque and consequently the speed increase.

In the third-mentioned method, the strength of the magnetic field is likewise varied; but, instead of varying the degree of excitation, the reluctance of the magnetic current is increased or decreased according to whether decreased or increased speed is desired. In one make of machine, this is accomplished by making the field poles hollow and placing within each a snugly fitting cylindrical iron core. By means of a system of bevel gears mounted on the frame and operated by a hand wheel, these cores may be moved inward or outward, thus providing a means for decreasing or increasing the reluctance.

In the multivoltage scheme, the field is connected directly across one set of supply lines while the armature through the medium of a suitable controller is connected successively between different pairs of mains. Actually this is a multispeed rather than a variable speed arrangement.

A more elaborate system is that employing variable voltage. In connection with this and receiving energy

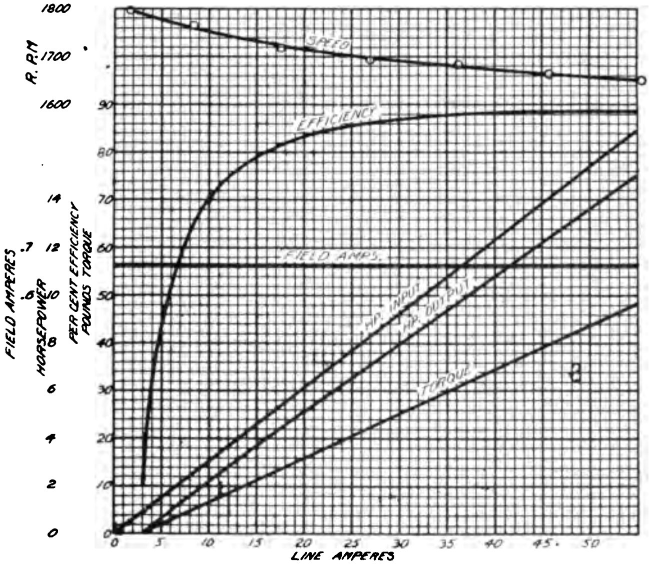


FIG. 151. CHARACTERISTICS OF A 230-V., 10-HP. SHUNT-WOUND MOTOR

from the same source as the motor field coils is used a motor-generator set, the generator end of which supplies current to the motor armature. It is thus evident that, as the electromotive force of the generator is varied, so is the speed of the motor.

THE SERIES MOTOR

As ITS name implies, the series motor is one in which the armature and field windings are connected in series in the manner indicated at A, Fig. 150; therefore, as

is obvious, the same current passes successively through the armature and field windings. Torque, as already explained, is proportional to the product of the armature current and the strength of the field and since the field strength increases in proportion to the armature current, the torque of a series motor increases as the square of

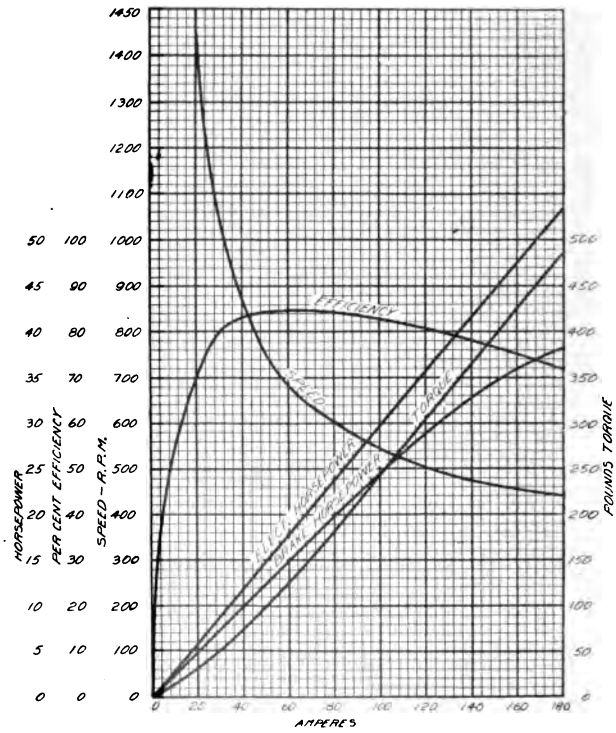


FIG. 152. CHARACTERISTICS OF A SERIES-WOUND MOTOR

the current flow. This, however, is true only up to the point of saturation of the field magnets; in proximity to and beyond this point, increase in current flow produces but a slight increase in field strength and as a result the torque will then vary only as the current. From the characteristics of a series-wound motor, as shown in Fig. 152, it will be seen how the torque curve varies inversely as the speed, thus rendering this type

of motor particularly applicable where the factor of steady speed is of minor importance, but where a high starting torque is desirable. As a result, the series-wound motor finds its greatest utility in the fields of electric traction, fan, crane or other work not requiring constant speed, but at all times insuring reasonable load, without which the motor would tend to run away, with consequent damage, not only to the motor, but also in many cases to the driven machine or machines.

The speed of such a motor is ordinarily varied by shunting the field, shunting the armature or, as in the case of electric railway work, by inserting an adjustable resistance in series with field and armature windings. With the latter method for a given load the motor draws the same current, regardless of speed, and the speed varies with the applied voltage.

After a series motor has been brought up to its normal speed by means of some form of starting rheostat, increase in speed at a given load may then be realized by inserting a resistance in shunt with the field, this action being due to the reduction in current flow through the field winding with accompanying decrease of field strength. On the other hand, assuming that all of the starting resistance has been cut out of circuit, connecting a resistance in parallel with the armature will result in a reduction of speed, an arrangement especially useful where low speed is desired at light loads.

Compound-Wound Motors

A compound-wound motor is a combination of a series- and a shunt-wound motor with the result that, as may be expected, it partakes of the characteristics of both of its component elements. Elementary connections of a compound-wound motor are shown at C, Fig. 150, while Fig. 153 illustrates the characteristics of such a machine.

Either one of two general schemes may be used to connect the field coils of a motor of this type. The series field may be made to assist the shunt field, in which case the machine is referred to as a cumulative compound-wound motor, or the series and the shunt

fields may be made to oppose one another. Under such conditions, the term "differential" is generally employed.

Cumulative compound-wound motors have the advantage of a heavy starting torque and an approximately constant speed although not as constant as that of the differentially-wound machine. As in the case of the shunt-wound motor, the speed of a differential compound-wound motor, due to the action of the shunt winding, tends to drop slightly with increase of load.

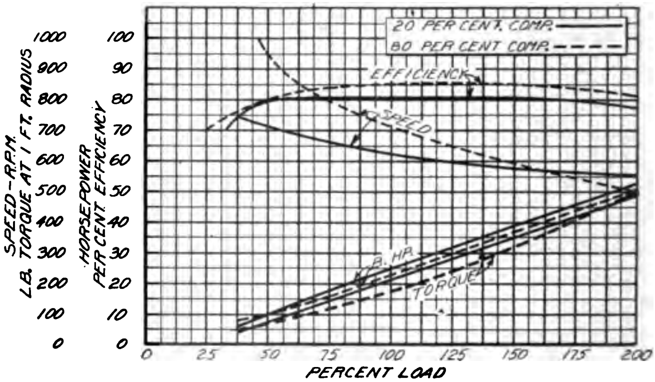


FIG. 153. CHARACTERISTICS OF A TYPICAL COMPOUND-WOUND MOTOR

However, as the load increases, the current flow through the series windings increases accordingly, as does also the effect on the field, due to the action of the series winding. But, because of the fact that shunt and series coils are wound in opposite directions, the effect of increase of series field is to tend to decrease the strength of the field acting upon the armature and, as a consequence, due to this slight weakening of the field, the speed of the motor increases. The current through the series winding is greater the heavier the load, hence the magnetization is reduced and practically perfect speed regulation obtained.

In general, speed and torque characteristics of a compound-wound motor are determined by the relative

influences of the series and shunt fields, so that by varying these factors in any ratio desired, speed and torque characteristics may be made to approach those of the series-wound motor with just sufficient shunt field effect to prevent running away of the motor at light loads. In a similar manner, they may be made to approach the constant speed characteristics of the shunt machine.

Questions on Chapter XIX

1. Why will a wire carrying current tend to move when placed in a magnetic field?
2. How is counter electromotive force generated? On what does its value depend?
3. What accounts for the difference between applied and counter electromotive forces?
4. If applied e m.f. is 220 v., armature resistance 3 ohms and counter e.m.f. 211 v., what would be the armature current? (3 amp.) $220 = 211 + 3x$ $9 = 3x$ $x = 3$
5. What would be the power delivered to the motor? (660 w.) 3×220
6. If the armature resistance be reduced to 2 ohms, what counter e m.f. would have to be generated, current still being 3 amp.? (214 v.)
7. What is the effect on speed of *increasing* armature resistance?
8. What three types of direct-current motors are in use, and how do they differ?
9. Why is a shunt motor commonly called constant speed?
10. How does shifting the brushes affect motor speed?
11. How does heating of the windings affect speed?
12. What is the objection to control of speed by armature circuit resistance?
13. How would you change the field of a shunt motor to increase its speed?
14. Will increasing the reluctance of the magnetic circuit raise or lower the speed of a motor? How is it accomplished?

15. For what kind of load is a series motor suited?
16. What is the effect of reducing load on a series motor?
17. How can the speed of a series motor be controlled?
18. What two arrangements of compound winding are used for motors?
19. Which gives better speed regulation?
20. For what kinds of work would you use motors with cumulative compound windings?

CHAPTER XX
DIRECT-CURRENT MOTORS
Control and Protective Devices

As ALREADY explained, the rate of current flow through the armature winding of a direct-current motor is dependent upon the value of the counter electromotive force and the resistance of the windings which ordinarily is comparatively low. It is thus evident that with the motor at rest and the counter electro-

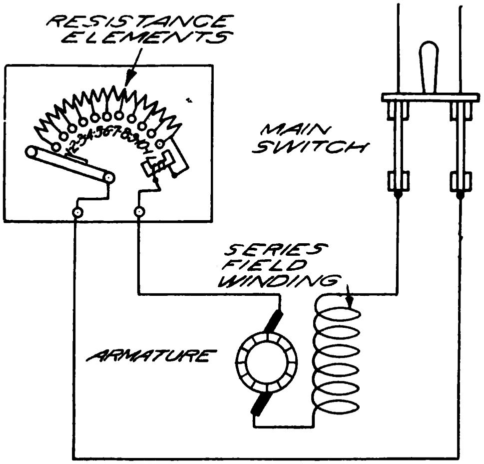


FIG. 154. STARTING BOX CONNECTIONS FOR A SERIES-WOUND MOTOR

motive force zero, excessively heavy current will flow through the armature at the time of starting unless some suitable resistance is introduced between the source of supply and the armature, arranged, however, so as to allow of being gradually (manually or automatically) cut out as the speed of the machine increases. Such an arrangement, commonly termed a starting box, or rheostat, used in connection with a series-wound motor is shown diagrammatically in Fig. 154. After throwing

in the main knife switch, moving the starting-box handle to point 1, permits a flow of current of small value through the machine windings and the starting-box handle, resistance elements and holding or no-voltage release magnet, and as a consequence the armature is slowly set in motion. Gradually the staring-box handle is moved to the right, making contact successively with contacts 2, 3, etc., and thereby cutting out of circuit portions of the resistance until point 11 is reached, when the motor, as

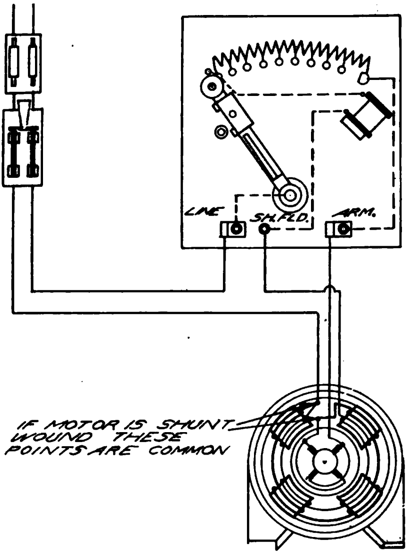


FIG. 155. TYPICAL STARTING BOX CONNECTION APPLICABLE TO BOTH SHUNT AND COMPOUND MOTORS

is evident, will be connected directly across the supply lines. When in contact with point 11, the starting-box handle is retained in place due to the energized state of the no-voltage release magnet, which, as may be seen, remains connected in circuit as long as any current passes through the machine windings. Frequently the no-voltage release magnet is connected directly across the supply lines so as to insure an unvarying degree of magnetization and holding power.

To stop the motor, the main switch is "pulled," the no-voltage release magnet "killed" and the starting-box arm caused to return to the position of start by the action of a coil spring with which it is equipped.

Typical starting-box connections applicable to both shunt and compound-wound motors are illustrated in Fig. 155. In this case, the no-voltage release winding is connected directly across the supply lines and in series with the shunt-field winding immediately the starting-box

FIG. 156. STARTING BOX FOR USE IN CONNECTION WITH LARGE MOTORS

handle is brought to the first point. This also brings the armature winding and starting box resistances in series across the supply lines and slowly the armature comes up to minimum speed; further movement of the starting-box handle to the right results in the cutting out of resistance in the armature circuit and the cutting in of resistance in the circuit made up of the no-voltage release and shunt-field windings, thereby gradually decreasing the flow of current through the shunt-field winding and the strength of the fields. It is thus evident that as the armature comes up to rated speed, acceleration is assisted in a slight degree by the introduction of the resistance in the shunt-field winding.

Where the motors to be controlled are of appreciable size, the use of a series of successively closed manually operated switches such as shown in Fig. 156 is pref-

erable. Interlocks are employed to prevent closure of these switches in any but the regular order.

Overload may be guarded against by the employment of a so-called overload release connected as shown in Fig. 157 in series with the armature. With an excessive flow of current, electromagnet S attracts its armature, the end of which, bridging contacts c and d, short-circuits no-voltage release magnet M. As a result, the starting-box handle is released and by means

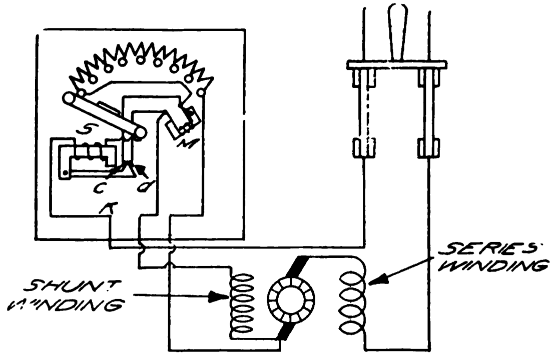


FIG. 157. SHOWING USE OF OVERLOAD RELEASE

of a spring provided for that purpose is brought back to off position, thus stopping the motor.

Operatives in industrial plants are as a rule not familiar with the proper mode of handling electrical machinery, and as a consequence of this, and frequently also due to indifference and carelessness, much damage is done to motors equipped with the regular form of manually operated starting box. To overcome this, remotely controlled starting boxes in which the acceleration of the motor is beyond the control of the operator are available. A scheme of connections for one of these devices is illustrated in simplified form in Fig. 158.

In this arrangement, two primary relays are employed, one for the closing of the switch which connects the armature and the starting resistance in series, and one for the closing of a second switch for the short-circuiting of the resistance when the motor has reached

rated speed. Pressing of the "start" button at the right energizes relay 1, and as a consequence, switch 1 is closed, thus cutting armature and starting resistance in series across the supply lines. An auxiliary series relay is directly below relay 1 energized by the flow of current through the armature circuit. At start, this current flow is comparatively heavy but decreases as the armature gains in speed. At a predetermined value of armature current flow (that is, armature speed), the plunger of

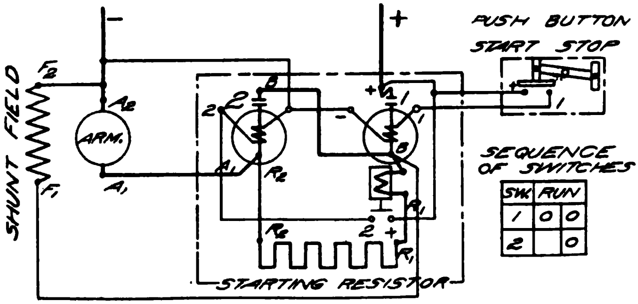


FIG. 158. SCHEME OF CONNECTIONS FOR REMOTE CONTROLLED STARTING BOX

the series relay drops, bridging contacts designated 2 and + in the diagram.

Accordingly, current is caused to flow through the windings of relay 2 which, being energized, closes switch 2, thus short-circuiting the starting resistance and cutting the armature directly across the supply line. The actual number of relays employed in an arrangement of this kind is dependent upon the number of starting resistance sections employed.

Protective Devices

The earliest protective device, and the one most generally used in connection with motors of small and medium capacity, is the fuse, which ordinarily consists of a short strip or wire of such metallic composition and sectional area as will allow the passage only of some predetermined maximum value of current. Current flow in excess of the rated capacity will cause the fuse to melt,

or as it is frequently termed "blow," opening the circuit and preventing further passage of current. Formerly fuses of the open type, that is, fuses mounted on porcelain bases and exposed, were used almost exclusively;

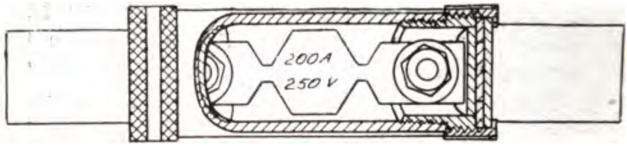


FIG. 159. ENCLOSED FUSE OF THE REFILLABLE TYPE

but, due to the fire hazard accompanying the blowing of such fuses, they have been practically superseded by those of the enclosed type such as illustrated in Fig. 159. Some of these when once blown are of no further utility, while others are of such construction as to allow renewal of the fuse element, thus providing an indefinite length of life for the containing cartridge.

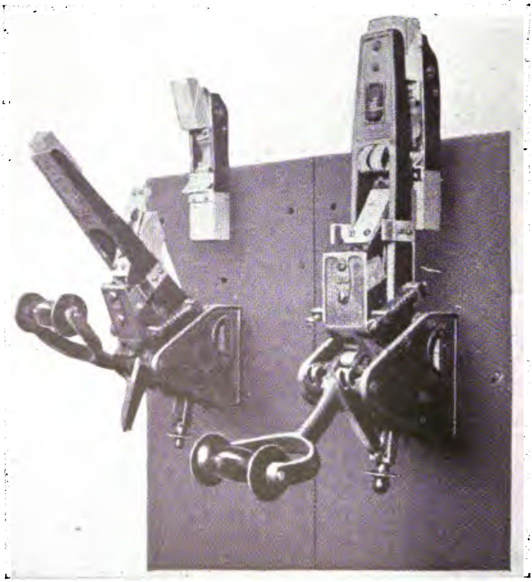


FIG. 160. TYPICAL CIRCUIT BREAKER

The primary advantage of the fuse lies in the fact that momentary overloads do not cause it to function, thus insuring continuity of service unless the overload continues for an appreciable length of time. When this occurs, however, the fuse will blow, the motor stop and service will be interrupted until a new fuse is inserted. In many plants, this may prove undesirable, and frequently costly.

To overcome this feature, various forms of mechanical circuit breakers such as illustrated in Fig. 160 have been developed. This is essentially a switch equipped with solenoids through which all or part of the current carried by the switch passes. Current in excess of a predetermined value energizes the solenoid to such an extent as to act upon a plunger, which is drawn into the solenoid, trips a catch, which in turn releases the switch member and thus opens the circuit. The action of such a circuit breaker is almost instantaneous once the flow of current exceeds the predetermined tripping value, unless the device is especially designed and constructed to do otherwise by means of a time-limit relay.

Questions on Chapter XX

1. Why is resistance used in starting a motor?
2. Should resistance be put in series with the field of a shunt motor when starting?
3. Would the box of Fig. 154 be suitable for a shunt motor?
4. Why is a no-load magnet used?
5. What is the harm of starting a motor too quickly?
6. What would happen if connections to field and armature were interchanged in Fig. 155?
7. What are the advantages of the fuse as a protective device?
8. Do you see any objection to the refillable type of enclosed fuse?
9. What is the advantage of the circuit breaker for a motor circuit?

CHAPTER XXI

DIRECT-CURRENT MOTORS

Efficiency Calculations

As in the case of any machine used for the conversion of energy from one form to another, the efficiency of an electric motor may be defined as the ratio of the output to the input. Expressed as a formula this is:

$$\text{Efficiency} = \text{Output} \div \text{Input}$$

although, as the output is equal to the input minus losses, we may also express the efficiency by means of the following form:

$$\text{Efficiency} = (\text{Input} - \text{Losses}) \div \text{Input}$$

To arrive at an accurate result account must be taken of all of the losses occurring within the machine. Some of these can be measured and others cannot, and as a consequence, satisfactory results are obtainable only by determination of both output and input under fixed load conditions. Measuring the rate of current flow in amperes in the machine leads and the electromotive force across the supply line, and multiplying these factors will give the input in watts.

In order, however, to determine the number of watts delivered at the pulley, or in other words, the output of the motor, the torque T expressed in pound-feet must be determined. Knowing this value, the work done in one revolution of the armature is equal to 2×3.1416 T ft.-lb. and in n revolutions per minute is equal to $2 \times n \times 3.1416$ T ft.-lb. Dividing by 33,000, the number of foot-pounds required to be expended per minute to develop one horsepower, gives as a quotient the number of horsepower developed, or

$$\text{Hp.} = \frac{2 \times n \times 3.1416\ T}{33{,}000}$$

But, as one electrical horsepower is equivalent to 746 w.,

this formula may be made to read directly in watts by the multiplication of 746, or

$$\text{Watts} = \frac{2 \times n \times 3.1416\ T \times 746}{33{,}000} = 0.142\ nT$$

This is the expression for the output. The efficiency formula, therefore, becomes:

$$\text{Efficiency} = \frac{0.142\ nT}{\text{watts input}}$$

As in the case of series-wound machines, the efficiencies of shunt-wound motors are generally dependent upon size, a machine of about ¼ hp. having a maximum efficiency of perhaps no more than 60 per cent, while machines of 30 hp. and larger may have efficiencies of 90 per cent and more. The efficiency curve of a compound-wound motor rises quite rapidly with increasing load, reaches a maximum value at a load somewhat less than the rated capacity of the machine, and then gradually declines.

Efficiency Calculations

If, from experimental data, the various losses in a motor operating at a given speed and voltage are known, the efficiency can be quite readily determined without measurement of the mechanical output. Let us assume that a 110-v., 50-amp. shunt-wound motor has a shunt-field winding resistance of 40 ohms, an armature winding resistance of 0.11 ohms, and a stray power loss at the prescribed speed and voltage of 700 w. (hysteresis, friction and eddy currents).

The input of this machine is equal to 50 times 110 or 5500 w.

Current flow through the shunt-field winding is equal to the applied voltage or 110, divided by the resistance of the winding, or 40 ohms, or 2.75 amp., which squared and multiplied by the value of the resistance, 40, gives as a result 302.5 w., the loss in the shunt-field winding.

At rated capacity the machine takes 50 amp., but as 2.75 amp. as indicated above are utilized to energize the shunt fields, 50 — 2.75, or 47.25 amp. pass through

the armature windings. The resistance of this winding, according to the specifications given is 0.11 ohms, thus making the armature $RaIa^2$ loss equal to 0.11×47.25^2, or 245.58 w.

The total losses are then equal to the sum of 700, 302.5 and 245.58 w., or 1248 w. We, therefore, have

$$\text{Efficiency} = \frac{5500 - 1248}{5500} = \frac{4252}{5500} = 0.773 = 77.3$$

per cent.

Let us further consider the case of a similarly wound motor but equipped with a series field and connected so as to be of the short-shunt compound-wound type. The series field resistance may be assumed to be equal to 0.05 ohms, thus introducing a loss due to this winding element of 0.05×47.25^2, or 111.6 w.

The total loss is in this case equal to that of the shunt-wound motor referred to above plus 111.63, or 1359.6 w., and the

$$\text{Efficiency} = \frac{5500 - 1359.6}{5500} = \frac{4140.5}{5500} = 0.753 = 75.3$$

per cent.

Questions on Chapter XXI

1. What is meant by the efficiency of a motor?
2. What are the losses in a motor?
3. What efficiency may be expected from a ½-hp. motor at full load? From a 20-hp. motor?
4. A 220-v., 75-amp. short-shunt compound-wound motor has at prescribed speed and voltage a stray power loss of 1035 w., an armature resistance of 0.015 ohms, a shunt-field winding resistance of 60 ohms and a series-field winding resistance of 0.09 ohms. Calculate the efficiency of this machine. (91.72 per cent.)

CHAPTER XXII

ALTERNATING-CURRENT MOTORS

Single-Phase Series and Synchronous Motors

ALTERNATING CURRENT motors may be classified as follows:

(a) Single-phase series motors.
(b) Synchronous motors.
(c) Polyphase induction motors.
(d) Single-phase induction motors.

From the discussion of direct-current machines, it was learned that the reversal of current flow through either armature or field windings would result in a reversal of direction of armature rotation, while a reversal of current flow through both armature and field windings has no effect upon the direction of rotation. Thus it is evident that an ordinary direct-current motor can be made to work on alternating current although practically operation is not satisfactory, this, however, due only primarily to the results of the inductive action of the windings. This is particularly well exemplified in the case of the shunt-wound direct-current motor. Because of the high inductance of the field winding, reversal of the applied electromotive force is followed by a gradual dying of the previously existing field current and a correspondingly slow growth of the reversed field current accompanied by a flow of current through the armature winding practically in phase with the applied electromotive force. As a consequence, a considerable phase difference exists between the current flowing through the field winding and that flowing through the armature winding and a negligible torque is developed.

In the case of the series-wound motor, however, a somewhat different condition exists. Armature and field windings are connected in series, reversal of current flow occurs simultaneously, and as a result, no phase differ-

ence between armature and field current can exis Fitting the series-wound motor with a laminated fiel structure and pole pieces and providing means to neu tralize armature winding inductance and preventin sparking has rendered this type of machine highly ap plicable to many forms of service particularly for th driving of small vacuum cleaners, office appliances dental engines, etc.

Cause of Sparking and the Remedy

Excessive sparking at the brushes is the most seriou difficulty encountered when attempting to operate an ordinary series-wound direct-current motor on alternat

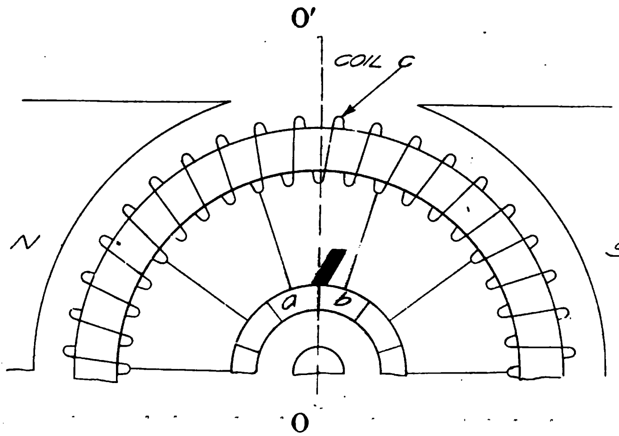
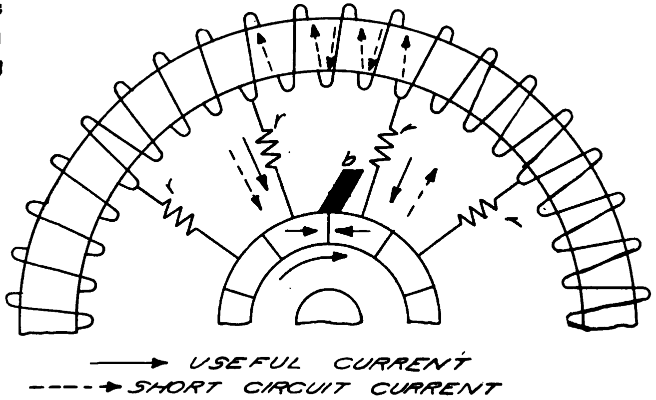


FIG. 161. SECTION OF TYPICAL RING-WOUND DIRECT-CURRENT ARMATURE

ing current. The cause of this is quite evident from a study of the action of these windings of this type of machine when carrying a current varying in value and alternately changing in direction.

Figure 161 illustrates an elementary diagrammatic section of a typical ring-wound direct-current armature placed between the two pole pieces N and S. As coil C passes through neutral plane O O′ it is short-circuited through the brush and commutator segments a and b, this short-circuiting taking place, as explained in the dis-

ussions on the principles of operation of direct-current enerators and motors, at the instant no magnetic lines f force are being cut, or in other words, at the time of inimum induced electromotive force. It is readily pparent, however, that when the fields are energized by lternating current, the resulting magnetization will also e alternating in direction and variable in intensity; so hat, instead of no electromotive force being induced in



IG. 162. SHOWING USE OF ARMATURE LEAD RESISTANCES

he short-circuited coil, this coil acts as a short-circuited econdary of a transformer carrying not only an induced lectromotive force, but also a comparatively heavy inluced current causing considerable sparking, destructive like to brushes and commutator.

The value of the electromotive force, and consequently current flow through such a short-circuited coil is proportional to the number of turns of wire in the short-circuited section, the maximum value of the pulsating field flux and the frequency of pulsation of this flux. In order, therefore, to realize an appreciable reduction in sparking, each of these factors must be reduced to a minimum value; and it is therefore apparent that in the design of a series-wound alternating-current motor, a maximum number of armature winding

sections (many commutator bars), minimum field flux per pole (many poles) and a comparatively low frequency such as 25 cycles per second be employed.

In addition, practice has indicated the need for other devices, such as the insertion of resistances and balanced choke coils in each commutator lead. In Fig. 162 is shown a section of an armature winding, each commutator lead of which is fitted with a resistance. A study of this diagram readily reveals the part played by these

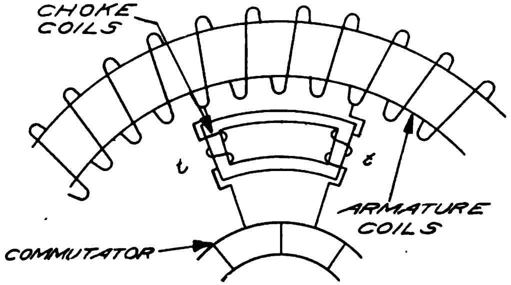


FIG. 163. SHOWING USE OF ARMATURE LEAD CHOKE COIL

resistances. Upon short-circuiting any particular coil such as C by brush b, the useful current is caused to pass through two of the resistance elements r and r connected in parallel, while the short-circuited current is also forced to pass through two of these elements but only when connected in series. Thus the short-circuited current is reduced to a minimum value.

Use of these resistances is, however, not without its disadvantages. Considerable loss of power takes place and much difficulty is usually encountered in placing them within the structure of the armature.

The means by which the choke coil is employed to reduce sparking in a series-wound alternating-current motor is well shown in Fig. 163. Connected in series with each commutator lead is the winding of a choke coil, which is so wound and connected with reference to the other mounted upon the same laminated wire core that their magnetizing actions with equal flow of current into or out of the armature winding are equal and

opposite in direction, thereby causing one to neutralize the inductive action of the other. As a coil is short-circuited by a brush, the local current resulting of necessity flows through the two windings of the choke coil; but because of the scheme of connections employed, the inductive action of the coil is brought into play and the current flow "choked."

The manner in which these choke coils are actually employed is shown in Fig. 164. Each commutator lead

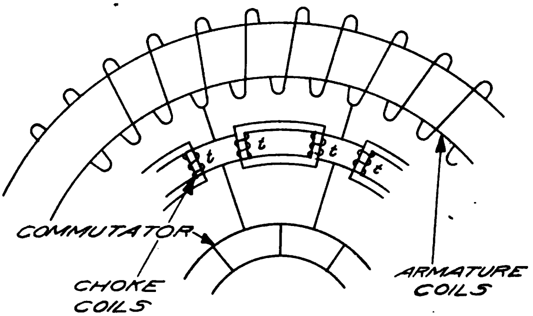


FIG. 164. APPLICATION OF BALANCED CHOKE COILS

is split into two branches and each branch contains a choke coil balanced against a similar coil in an adjacent lead.

Synchronous Motors

When operating two or more direct-current generators in parallel, the total load may be proportioned among the various units by the proper adjustment of the field rheostats of the respective machines, an increase of field resistance resulting in a decrease of load. With machines of the same capacity, the load is generally equally divided; while if machines of various ratings are employed, the load must be proportioned among the several machines in such a way that each carries its proper share.

Alternating-current generators operating in parallel cannot, however, have their loads adjusted in this manner. Proper division of load between these machines is controlled by their prime movers. This is sometimes

accomplished by controlling all the engines from a common throttle valve, although the more usual scheme consists in running all the machines except one with their stop valves wide open and their governors fixed, so that the remaining engine may care for any variations in the common load.

Figure 165 is a conventional diagram representing two alternators connected for parallel operation. If, for

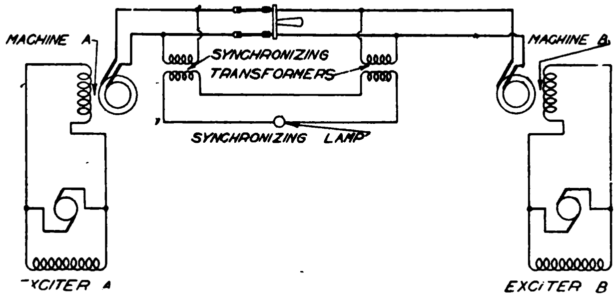


FIG. 165. TWO ALTERNATORS CONNECTED IN PARALLEL EITHER ONE OF WHICH MAY OPERATE AS A SYNCHRONOUS MOTOR

some reason, the prime mover of machine B fails, not only will the load carried by this unit be thrown onto machine A, but machine B will become a motor and be driven by machine A, thus exemplifying an alternator driving a synchronous motor; hence, any machine usable as an alternating-current generator may be operated as a synchronous motor and vice versa.

Starting of Synchronous Motors

All single-phase synchronous motors require some external means of starting, such as a small steam or other engine, or a small alternating-current induction, or direct-current motor. These starting units may either be belted or geared to the synchronous motor, or, when a motor is used, this may be mounted directly on the shaft of the synchronous motor.

Polyphase motors can, however, very readily be started at no load without any auxiliary starting motor.

The application of the alternating current directly to the stationary armature without field excitation will result in a rotating magnetic field about the armature core. The eddy currents thereby produced in the pole piece will exert a torque on the armature and cause it to speed up to synchronism. Usually some form of starting compensator is employed for reducing the applied voltage during the starting period. At synchronism, the field current is thrown on and the motor runs as a synchronous motor.

When a starting motor is used, the synchronous motor is brought up to speed, and its field normally excited, the motor is synchronized and connected to the supply lines in exactly the same manner that an alternating-current generator is synchronized and placed in parallel operation with one already running.

Speed

Synchronous motors are practically constant speed machines. When overloaded, shunt-wound direct-current, and alternating-current induction motors will gradually slow down until stalled. Such is not the case with synchronous motors. The per cent of overload any such motor will carry is fixed for each individual machine, and any increase of load above the specified maximum figure will cause the motor to "fall out of step," that is, out of phase relation with the supply voltage, and stop, after which the load must be disconnected and the motor again brought up to proper speed, synchronized and thrown onto the supply lines.

Synchronous motors are so called because they operate in synchronism with their driving generators, so that under all conditions of operation, the speed of such a motor bears a definite relation to the speed of the driving generator.

Alternating-current generators and synchronous motors being interchangeable, the speed of the latter may, therefore, be calculated in the same manner as that of the former.

Excitation

This, as in the case of alternators, may be supplied by a common exciter used in connection with a number

of synchronous motors or alternators or may, as is usually done, be supplied by a separate machine, the armature of which may be mounted on an extension of the motor shaft. Each machine requires, at no load, a definite exciting current under which conditions a minimum number of amperes will be drawn from the line. We find, however, by plotting the number of amperes of line current against the corresponding number of amperes of exciting current, that with any deviation

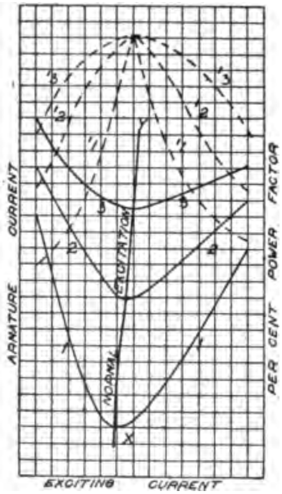


FIG. 166. PHASE CHARACTERISTIC OR V CURVE OF SYNCHRONOUS MOTOR

from the normal exciting current an increase of line current will result. If various values of exciting current and corresponding values of line current readings be plotted against each other, a V-shaped curve as shown at 1 in Fig. 166 and known as the phase characteristic will be obtained. Repeating this plotting of readings for half and full load, we get curves 2 and 3, Fig. 166.

From this it would appear as if an increase or decrease of field excitation from normal would result in a greater consumption of energy without any additional load on the motor. This, however, is not the case. If at the time of obtaining the phase characteristic read-

ings, power factor readings had also been taken and plotted, we would have obtained curves such as shown by the dotted curves '1, '2, and '3, thus indicating that even though the line current becomes excessive, the actual energy consumption is but little more at extremes of excitation than at normal excitation. At high values of line current, the power factor is necessarily extremely low.

Another interesting point which the use of a power factor meter will bring to light is that, with an exciting current below normal, the line current lags behind the electromotive force, while with an exciting current greater than normal the line current will lead the electromotive force. In both cases there will be an increase in the line loss.

Power Factor Correction

To secure the greatest economy both in first cost and operation of alternating-current machinery, transmission and distribution lines and so forth, it is imperative that the power factor of the system be as near unity as possible. This, however, is a condition not easily obtained, as the greater share of the load carried by the average station is of an inductive nature, such as transformers and induction motors, resulting in a low, lagging power factor.

The current taken by a synchronous motor will lead the electromotive force when the exciting current of the motor is greater than normal or, as technically stated, "an over-excited synchronous motor will draw a leading current," thus enabling it to neutralize wholly or in part the lagging effect of an inductive load.

Hunting

One of the greatest difficulties encountered in the operation of synchronous motors, especially if these be supplied with current generated by machines driven by reciprocating engines is the tendency to "hunt," resulting in a considerable voltage disturbance over the entire system. This phenomena is similar to the behavior of a steam engine under the control of an oversensitive governor.

With a sudden increase of load, the speed of a synchronous motor momentarily slows down and falls behind the generator in phase; and when the speed has dropped sufficiently to allow the machine to take in the power required to operate it, it is still running somewhat below synchronism. Further reduction in speed takes place and as a result an excess of power is taken from the supply line which causes a decided increase in speed above synchronism. It then gains on the generator in phase until the intake of power is less than that required when the speed of the motor again drops and the cycle is repeated. This oscillation of speed above and below synchronism is termed "hunting" and is accompanied by a varying current consumption and by a rapid rise and fall of electromotive force between the motor terminals.

Hunting may frequently be traced to the periodic changes in driving-engine speed. Thus the engine momentarily increases in speed as the steam acts upon its piston and diminishes its speed during the intervals between strokes. This cause of hunting may, however, be readily eliminated by the employment of turbine-driven generators.

Hunting may be entirely eliminated or at least greatly reduced by the use of a loose flywheel on the motor shaft or by the employment of "dampers," which consist of rectangular copper frames driven into place under the overhanging tips of two adjacent poles. Such a damper is provided between each pair of adjacent poles, all around the field, both in the alternator and in the synchronous motor.

Another form of damper found quite effective is the squirrel-cage damper. Heavy bars of copper are placed in slots at the surface of the poles and their ends bolted to two closed copper rings, so as to short-circuit all the bars.

The principle of the damping action is that the shifting magnetic field sets up an induced current in the short-circuited frames or bars of the dampers, and these currents react on the magnetic field so as to oppose the shifting of the flux and thereby dampen the hunting oscillations.

Use of Synchronous Motors

Synchronous motors are applicable only where no high starting torque is necessary, where frequent starting and stopping is not required, and where constant speed is desired. Their field of usefulness is, therefore, somewhat limited. Due to the effect which a variation of its field excitation has upon its power factor, the synchronous motor is extensively used for the purpose of correcting a low, lagging power factor, such as is caused by heavy transformer and induction motor loads. Many central stations supplying both alternating and direct current generate the former only, and obtain their supply of direct current either from direct-current generators driven by synchronous motors, or from synchronous converters. Under proper conditions of operation, the field excitation of these synchronous machines is maintained at its normal value, but with a heavy inductive load on the system, creating a low, lagging power factor, overexciting the fields of the synchronous machines will cause the motor to draw a leading current, and thereby improve the power factor.

When there is no use for the mechanical power in the generating station, synchronous motors are frequently connected to the distribution system at some distant point and allowed to float on the line with an overexcited field, for the express purpose of correcting a poor power factor; and in order to prevent the idle operation of such machines, the managements of central stations many times offer special inducements in the form of lower rates to power consumers who will use synchronous motors instead of induction motors.

When used for the express purpose of power factor correction, synchronous motors are generally termed synchronous condensers.

Balancing Action

The fact that a synchronous motor draws a leading current when overexcited and that the value of this leading current is increased with an increase of overexcitation, gives to this type of polyphase machine the capability of restoring a balance to an unbalanced polyphase

circuit. When a slightly overexcited motor is connected to the terminals of a balanced or an unbalanced polyphase system, all phases of the motor armature draw a leading current. That phase winding, however, which is connected across the terminals of lower voltage, draws a greater leading current than the other windings, because its overexcitation is relatively higher, hence the compounding tendency of the leading current is more marked in this phase than in the others, and the voltage

FIG. 167. TYPICAL 200-HP. SYNCHRONOUS MOTOR WITH ROTOR SHIFTED OUT OF FRAME

thereof is increased. This action tends to balance the circuit, not only in voltage but in current as well, because combinations of leading and lagging currents give reduced resultant currents.

ADVANTAGES AND DISADVANTAGES

THE SYNCHRONOUS MOTOR, especially in large units, possesses a number of features which make its use at times preferable to that of the induction motor. These

may be briefly summed up as follows: (a) Unvarying speed at all loads; (b) Power factor variation at will by change of exciting current; (c) The current in the armature can be made to lead the electromotive force by overexciting the field magnets, thus producing the same effect as a large condenser. The leading current in the armature can be used to neutralize the unfavorable effects of inductance in other parts of the system; (d) The synchronous motor is cheaper to build, especially for low speeds, than the induction motor; (e) Its efficiency is generally higher than that of the induction motor; (f) It is specially adapted to high voltage winding.

This type of motor has on the other hand, the following disadvantages: (a) It is not adapted to work requiring variable speed; (b) It has small starting torque, hence is not suitable for work where the load at starting is large; or frequent starting is required; (c) It has a tendency to "hunt"; (d) It requires an exciting current which must be supplied by an outside source; (e) It requires skillful and intelligent attention.

Questions on Chapter XXII

1. What is the reason for the name "synchronous" motor?
2. What will be the r.p.m. of an 8-pole synchronous motor connected to a line whose current has a frequency of 60? (900 r.p.m.)
3. What speeds are to be gotten with synchronous motors on a 60 cycles per second system? (2, 4, 6, 8, 10 poles.) (3600, 1800, 1200, 900, 720 r.p.m.)
4. What speeds can be gotten on a 25 cycles per second system? (1500, 750, 500, 375, 300 r.p.m.)
5. What happens when a synchronous motor is overloaded?
6. What is the effect of underexcitation of a synchronous motor on the power factor of a circuit to which it is connected?
7. If a synchronous motor is carrying full load with normal excitation and the load is reduced, what, from Fig. 166, will be the effect on the power factor of the circuit?

8. What prevents the use of the ordinary direct-current motor on an alterating-current circuit?
9. How are synchronous motors started?
10. What is the cause of hunting? How corrected?
11. What is a rotary condenser?
12. Could a single-phase synchronous motor be used on one leg of a polyphase circuit to balance the system? Would it have an effect on the power factor of all phases?

CHAPTER XXIII

THE INDUCTION MOTOR

Principle of Action, Windings, Connections, Starting and Speed Control

THE induction motor has the advantage of being free from commutator and brushes, so that there is no chance for sparking and this is of importance in places where a fire might be started by sparks. It is of simple construction, not likely to get out of order, and easily controlled from a distance, as the only connections to the motor are the three leads, unless speed control is secured by connections to the rotor, in which case six connecting leads would be needed, but the resistances and starter or controller could be placed at any point desired.

Action of the induction motor is similar to that of the transformer, and the two parts of the motor are sometimes spoken of as the primary and secondary, although more properly called the stator and rotor. Usually current is supplied to the stator or stationary part, and the secondary, rotor or moving part has current generated in its short-circuited windings by induction. In a few special designs, current is supplied to the rotor which then becomes the primary, and the stator acts as the secondary of the transformer.

To understand the action of the motor it is necessary to get the idea of the rotary magnetic field. If we have a 4-pole machine with one pair of poles excited, as shown in Fig. 168, A, a bar of iron will aline itself with the magnetic field, and the same would be true of a round iron core magnetized by an electric current so that magnetic poles were formed in the core. If the other pair of poles is excited as in B, the bar will aline itself with their field. If both sets of poles are excited, the bar will take the direction of the resultant field standing half way between the poles. If 2-phase currents at 90 deg. are used to excite the two sets of poles, it is

evident that the excitation will be varied, increasing and decreasing in such a way that the bar will be made to revolve following the revolving magnetic field. Or, if there were three sets of poles, and a 3-phase system of currents at 120 deg. were used for excitation, there would still be a revolving field, but steadier in intensity.

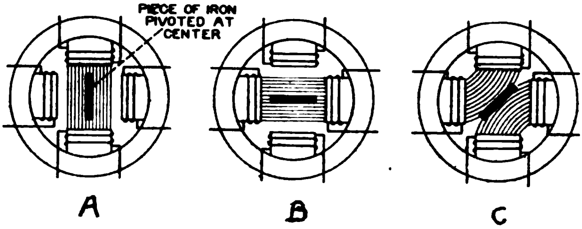


FIG. 168. PRINCIPLE OF ROTARY MAGNETIC FIELD

Instead of the bar of iron, a core is used built up of sheets to prevent eddy currents, and on this is placed a winding of copper bars in slots, or of wound coils, the secondary current of the transformer action serving to produce magnetic poles in the core.

The stator winding is of coils spaced for two or

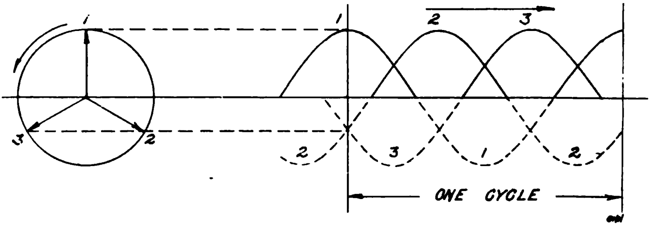


FIG. 169. RELATION OF CURRENTS IN 3-PHASE MOTOR

three phases, much the same as those in the armature of an alternating-current generator, each magnetic pole having one coil of each phase. The winding of the rotor in the simpler motors is a series of bars, inserted in slots in the core and short circuited at the ends by copper rings, being known as the squirrel-cage type. To study the action, consider the rise and fall of the currents in a 3-phase system as indicated in Fig. 169, and the result-

ing action in a 2-pole motor with one coil of each phase to a pole as shown in Fig. 170.

When No. 1 current is at a maximum and positive, above the line, No. 2 is at half its maximum value, negative and decreasing, and No. 3 is at half its maximum, negative and increasing. When No. 1 is at 0, No. 2 is at

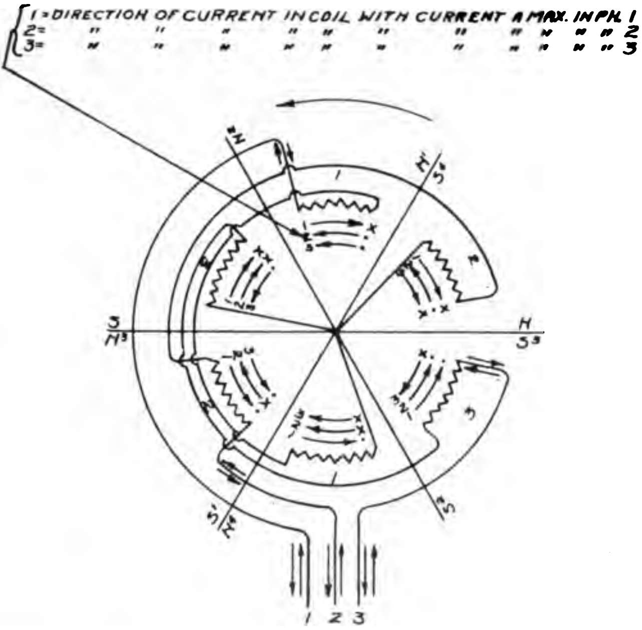


FIG. 170. CURRENT ACTION IN 2-POLE, 3-PHASE INDUCTION MOTOR

half its maximum positive and increasing, and No. 3 is at half the maximum, negative and decreasing. Always when one current is at its maximum, the other two are at half their maximum value and of the opposite sign; and when one current is at zero, the other two are equal and opposed, one being positive and the other negative.

Turning to Fig. 170, the windings are in three groups, one for each phase, i.e., one coil per phase per pole, hence one pole consists of three coils, each carrying the current of one phase. The coils are connected in

star, that is, have a common junction at the center. For the first condition, consider that the current is flowing into coil 1 of the top group, down to 1 of the bottom group, thence to the junction point, returning through top coils 2 and 3 to lines 2 and 3 of the supply circuit. The symbol • denotes that current is flowing away from the observer into the paper, and symbol x that current is coming toward the observer, out of the paper as indicated by the arrows 1 inside the coils. All coils above the horizontal diameter are carrying current down and all below the horizontal, up. If current 1 is at a positive maximum, currents 2 and 3 are opposite and equal, and resultant magnetic poles will be formed at N and S on the horizontal diameter.

As current 1 falls, 2 decreases and 3 increases, the effect on the resultant magnetic poles changing accordingly so that the N pole will rise and the S pole will fall from the horizontal, and when current 2 is 0 and current 3 equals current 1 but in the opposite direction, the magnetic field will be along a line through the middle of coil 2. This action will continue, and when current 3 is a negative maximum, the magnetic poles will have shifted to a line between coils 2 and 1 at points N′ and S′.

When current 2 reaches a positive maximum, the poles will have moved to N^2 and S^2, and so on, so that the rotation of the field is in a counter-clockwise direction. With any current a maximum, the poles are on a diameter perpendicular to the plane of the coils carrying that current, and as the current in any coil is reversed, the magnetic field is reversed. When current 1 is a negative maximum, the poles will be at N^3 S^3, and when current 1 again comes to a positive maximum, the poles will have come around to N S again. The magnetic field thus makes one revolution for each cycle for a 2-pole motor. For a multiple-pole motor, the speed of the magnetic field, r.p.m., will be equal to 60 times the frequency divided by the number of pairs of poles. The speed of the rotor will be nearly equal to that of the field, the difference being the slip and depending on the load that the motor is carrying and the resistance in the rotor circuits.

If there were no slip, there would be no lines of force cutting across the conductors of the rotor, hence there would be no e.m.f. generated and no current in the rotor windings. This is impossible, but it follows that the greater the slip, the greater will be the e.m.f. and the current in the rotor, hence as load is applied to the rotor, the slip will increase, allowing the rotor to carry greater current and thus to have greater torque. The e.m.f. and frequency in the rotor are always, however, small. When the rotor is stationary, the frequency in its windings will be the same as that of the stator; if the rotor were running in synchronism with the magnetic field, the frequency would be zero. The actual frequency is the line frequency times the percentage of slip, slip being reckoned as a percentage of the stator field speed. For small motors up to 5 hp. the slip will be 5 to 6 per cent, while in larger motors it will be as low as 1 per cent.

The e.m.f. generated in the rotor windings is also equal to the stator e.m.f. times the percentage of slip, this giving the total amount available to set up current in the rotor circuits, whether the rotor be short-circuited or closed through outside resistance. This point is important in connection with speed regulation.

Starting Devices Single-Phase Motors

For small motors it is possible to throw the motor directly upon the lines and allow it to come to speed, but this involves a great strain on the mechanical parts of the motor and on whatever shafting and belts may be connected, so it is not used for motors of over 5 hp. For the larger sizes some form of starter is used to bring the motor to speed more gradually, and with less strain.

The most commonly used starter consists of autotransformers having taps brought out so that the voltage to be applied at starting can be varied as desired, a double throw switch to give starting and running positions and a case in which the switch and sometimes the transformers are enclosed. Figure 170A shows the arrangement with the various parts labeled.

For high starting torque, wound-rotor induction mo-

tors with secondary-resistance starters are frequently employed. These starters consist essentially of variable resistances connected in series with the rotor windings. They may or may not be incorporated with an auto-transformer but if so the primary switch is interlocked in such manner as to allow operation of the auto-transformer switch only when all of the secondary resistance is in circuit.

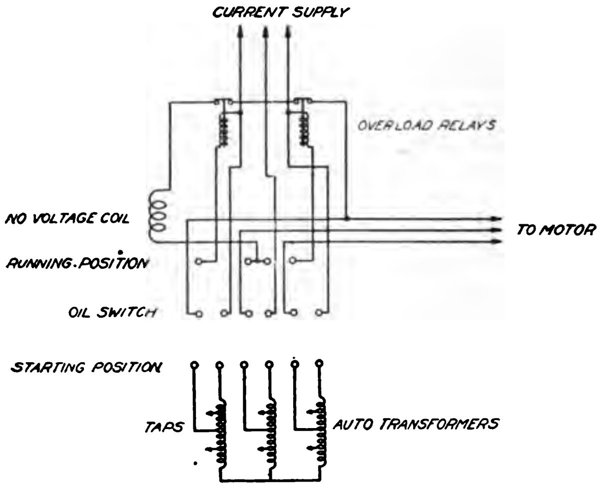


FIG. 170A. DIAGRAM OF CONNECTIONS FOR 3-PHASE STARTING COMPENSATOR

By the introduction of resistance in series with the rotor windings the speed may be reduced without change of torque. At constant torque, the total power drawn from the line will be constant and the loss of mechanical power due to reduced speed appears as heat dissipated in the regulating rheostat. This method although ordinarily used only where the periods requiring speed variations are comparatively short and the motor runs at normal speed most of the time, is one giving a wide range of speed. It is, however, wasteful, especially at low speeds.

For three-phase motors of 15 hp. rating and less operating at potential not exceeding 550 v., the star-

delta scheme of starting may be employed. In this arrangement as shown in Fig. 170B, six winding leads are brought out to a special form of so-called "star-delta" starting switch.

Initial position gives a star connection, the intermediate blades temporarily shorting the three upper

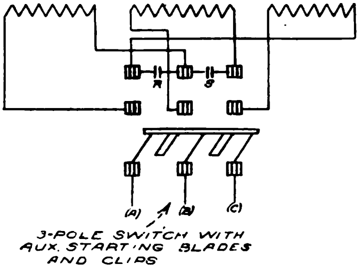


FIG. 170B. DIAGRAM OF CONNECTIONS SHOWING SPECIAL STARTING SWITCH

terminals together, while the final or running position is in delta. This has the effect of placing on the motor about 58 per cent of full voltage and consequently reducing the starting torque ⅓ its normal value on full voltage. For this reason the usefulness of this scheme is limited to cases where such low starting torque is sufficient to move the load.

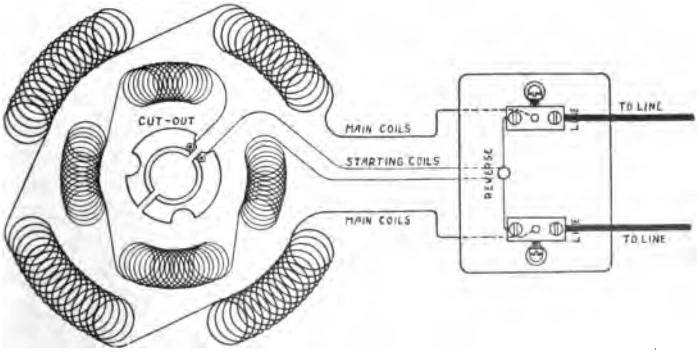


FIG. 171. SINGLE-PHASE MOTOR ARRANGED FOR SPLIT-PHASE STARTING

THE STRAIGHT single-phase induction motor, unless provided with a phase-splitting device or a shading coil, develops no starting torque when its rotor is not revolving, and as a consequence occupies but an exceedingly limited field. With the use of a phase-splitting device or a shading coil, this disadvantage is, however, eliminated.

Where split-phase starting is employed, the motor is

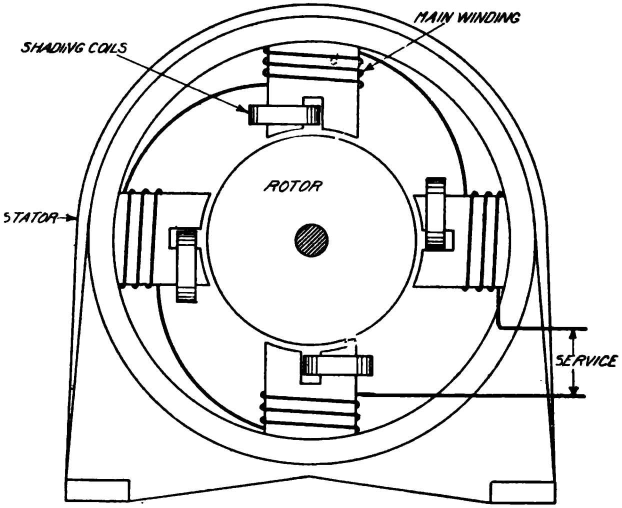


FIG. 172. METHOD OF USING SHADING COILS FOR STARTING SINGLE-PHASE MOTORS

fitted with two distinct windings, displaced as shown in Fig. 171, 90 deg., and known as the starting winding and the running winding. The starting winding circuit is so arranged as to possess considerably more inductance, capacity or resistance than the running winding, with the result that a rotating magnetic field is created and the rotor enabled to start. After the rotor has reached synchronous speed, the starting winding is cut out of circuit, which operation is generally accomplished automatically by means of a centrifugal switch embodied within the revolving member.

Motors designed for starting on the shading coil principle have their pole pieces fitted with short-circuited bar windings in the manner indicated in Fig. 172. The flux created by the flow of alternating current through the main winding passes through the pole pieces and induces in the shading coils a secondary current, the resulting magnetic field of which tends to oppose that portion of the pole flux producing it. Due to the fact that therefore the flux in the unshaded portion of the pole pieces reaches its maximum value at a different instant from that emanating from the shaded portion and the displacement of the two halves of the pole pieces, a revolving magnetic field is established, thus enabling the motor to pick up speed.

This scheme, like that of the split-phase arrangement, is applied only to motors of fractional horsepower capacity.

Due to their very nature, and as their names implies, induction motors tend to draw a lagging line current. As a result, and especially where many small and underloaded induction motors are installed, extremely low lagging power factors will be encountered. To eliminate this trouble and not only improve the lagging power factor, but also to provide a machine drawing a leading line current, one manufacturer has placed on the market a so-called unity power factor motor. This machine, which is self-starting, without clutches or other auxiliary devices, is said to possess approximately unity power factor at full load, with leading power factors at loads from zero to 100 per cent of rating.

An elementary diagram of connections of this type of motor is shown in Fig. 173. Two windings, a main and a compensating winding, are employed, the former used to produce the main field flux, while the compensating winding is utilized exclusively for the control of the power factor.

The main winding is of the usual squirrel-cage construction and occupies the bottom of the slots, while the auxiliary winding occupies the space above, a magnetic separator made of soft rolled steel bar being placed between the two. The auxiliary winding is connected

to a standard form of horizontal commutator, which in turn is provided with two sets of brushes. One of these, the main pair, is placed in the axis of the main stator winding and is interconnected, giving repulsion motor characteristics; the auxiliary pair of brushes is placed at right angles to the main stator winding and is connected in series with it. The auxiliary stator

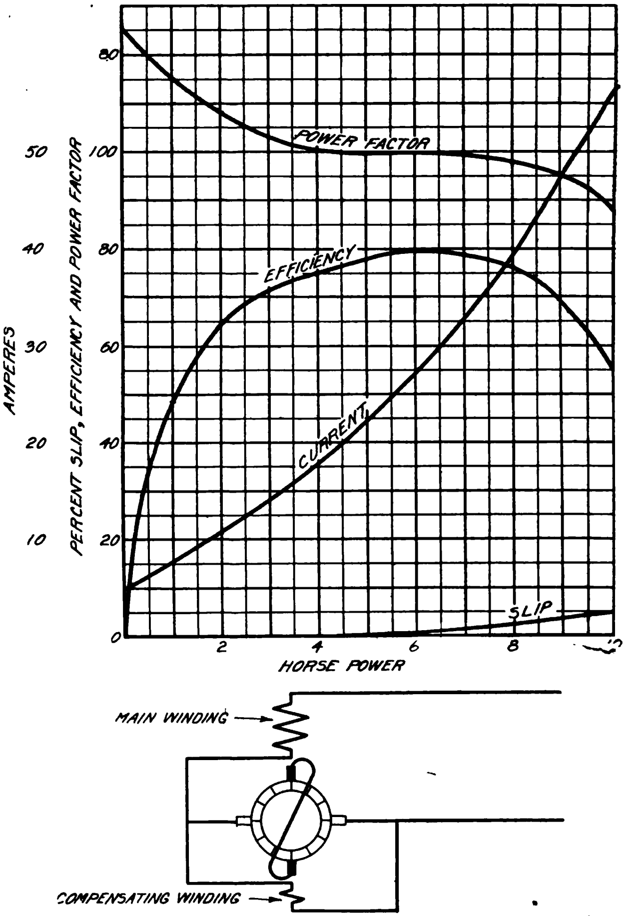


FIG. 173. ELEMENTARY DIAGRAM OF CONNECTIONS AND CHARACTERISTICS OF A UNITY POWER FACTOR MOTOR

winding is arranged to be automatically connected in parallel with the auxiliary brushes at a predetermined speed, and while this connection improves the power factor and the speed characteristics, it is not essential to the operation of the motor. Should the automatic switch fail to close, the machine would still operate

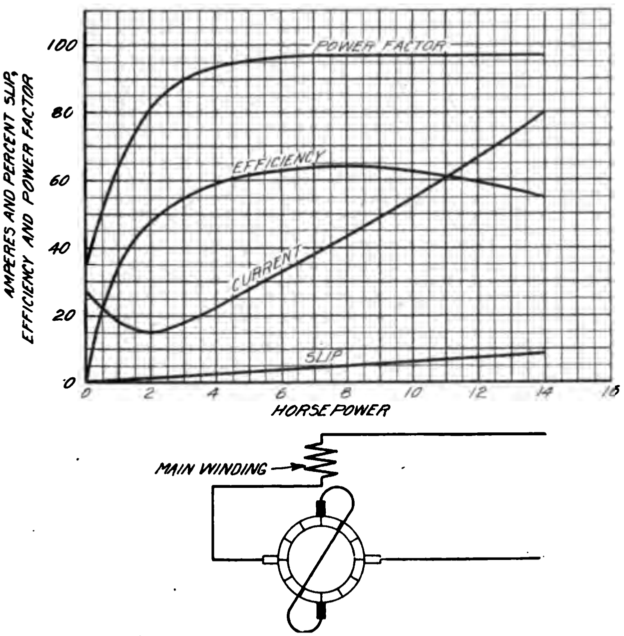


FIG. 174. DIAGRAM OF CONNECTIONS AND CHARACTERISTICS OF UNITY POWER FACTOR MOTOR WITH COMPENSATING WINDINGS DISCONNECTED

satisfactorily but with reduced power factor and efficiency. The result of this action is shown in Fig. 174. The machine will operate and carry full load if, after the motor has reached rated speed, all the brushes were removed. It would then operate as a squirrel-cage induction motor with characteristics as shown in Fig. 175.

Motors of this type are particularly well adapted for service requiring power factor correction, and on account of their inherent torque and speed characteristics are many times preferable to the synchronous motor.

An alternating-current motor which, like the series-wound direct-current motor, possesses high starting torque with increasing speed, is the straight repulsion motor. This motor, which is well adapted to such service as the driving of fans, printing presses, blowers and other machines requiring a constant torque, has power

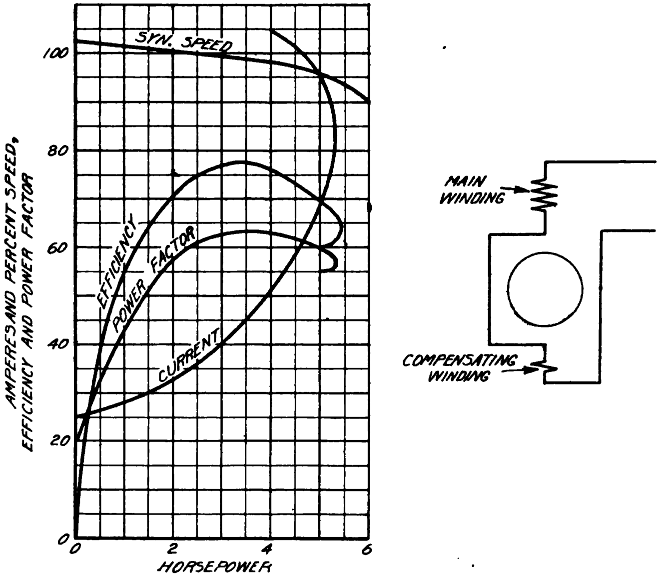


FIG. 175. DIAGRAM OF CONNECTIONS AND CHARACTERISTICS OF UNITY POWER FACTOR MOTOR WHEN ALL BRUSHES ARE REMOVED

factor characteristics more nearly approaching unity than the induction motor.

In the repulsion induction machine, two windings, a main winding and a compensating winding, are employed, the latter connected as shown in Fig. 176 to compensating brushes bearing upon the commutator in the manner indicated. A main or energy set of brushes having approximately the same angular position in relation to the stator winding as the energy brushes of the straight repulsion motor are also employed.

Efficiency, power factor and speed-torque curves shown herewith graphically illustrate the operating characteristic of a typical repulsion induction machine. The starting torque of a motor of 5 hp. rated capacity and less is 250 per cent of full load torque at all frequencies and of machines of 7½ hp. and more 200 per cent of full load torque. The maximum running torque is about 300 per cent of the starting torque, and as a

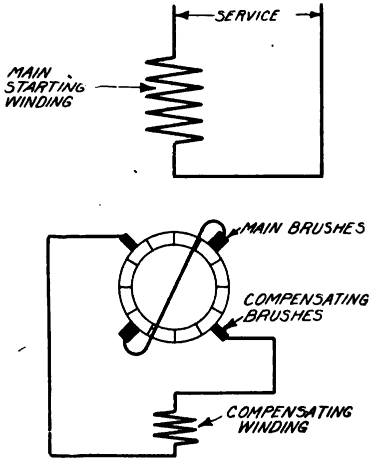


FIG. 176. DIAGRAM OF CONNECTIONS OF A REPULSION-INDUCTION MOTOR

consequence the motor will accelerate any load it will start.

Power factor values, as may be seen, tend to approach unity throughout the rated capacity of the machine with, however, a slight drooping of the curve at extremely light and full loads.

The efficiency gradually increases with load with the curve between 75 and 125 per cent load quite flat.

Ordinarily the motor is practically a constant speed machine, although variable speed is obtainable by the insertion of a rheostat in series with the energy brushes or by an auto-transformer connected in the supply line to vary the applied voltage.

A further modification of the repulsion-induction motor is the repulsion-starting, induction-running machine, which has a single winding isolated from an armature similar in form and construction to the type used in direct-current motors. Brushes are provided and electrically interconnected by a metal supporting arm, the number employed being the same as in a given direct-current motor with a like number of pole pieces.

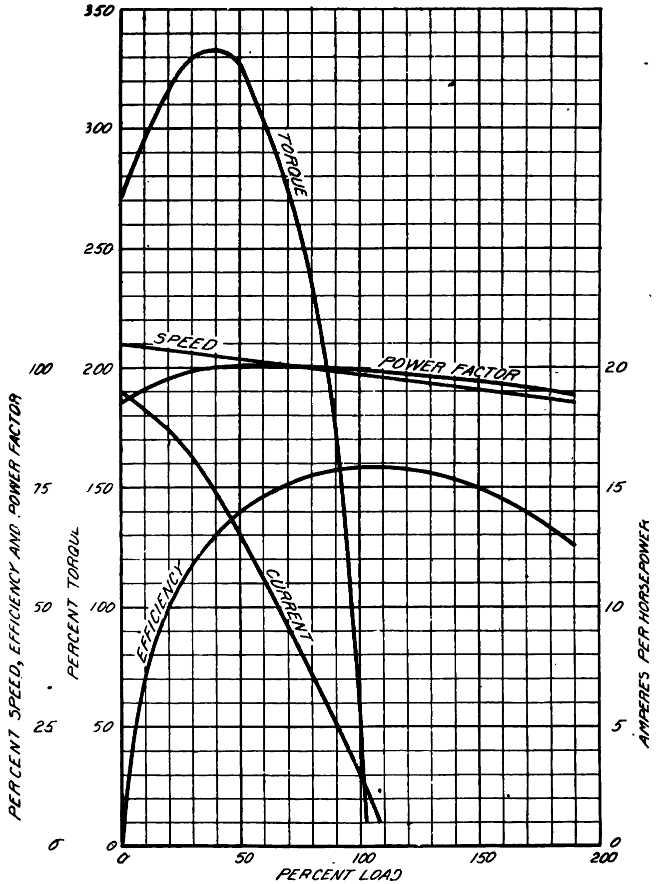


FIG. 177. CHARACTERISTICS OF A REPULSION-INDUCTION MOTOR

Reaction of the stator currents upon the rotor winding induces rotation, and as soon as synchronous speed is reached, a centrifugally operated device short-circuits the commutator, thus providing essentially a machine of the squirrel-cage type.

The speed of this machine is practically constant, although the power factor is not nearly as satisfactory as that of the repulsion-induction motor. As shown in Fig. 178, its efficiency curve rises quite gradually from

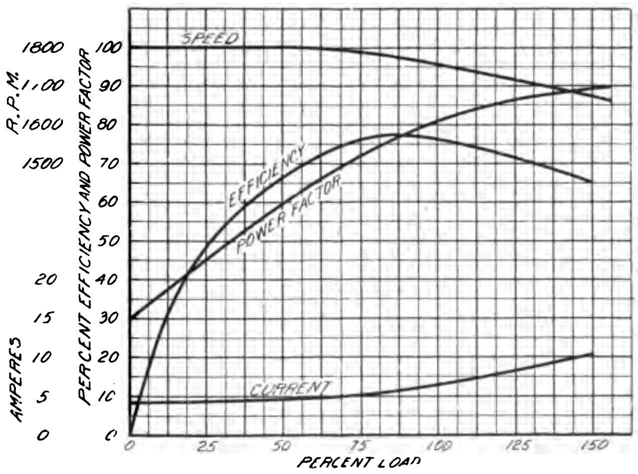


FIG. 178. CHARACTERISTICS OF A REPULSION START INDUCTION RUNNING MOTOR

zero to about 80 per cent load, after which it declines in the manner indicated.

Motors of this type are well adapted to service similar to that for which the direct-current shunt-wound machine may be employed, and have the advantage of this machine in a considerably greater starting torque. It is not well suited for adjustable speed work.

Except for a laminated field structure, series-wound alternating-current motors are practically the same in construction as direct-current machines of the same type, and possess similar characteristics. They are primarily intended for light work, such as the driving of

fans, blowers, drills, etc., although due to their powerful starting torque and adaptation of speed to load, they are utilized in traction and similar work to a limited extent.

Care and Testing

Induction motors require little care beyond seeing that the bearings are supplied with oil or grease, but in case trouble develops, the hunting out and remedy should be gone about systematically to lessen the labor and make sure that the source of the trouble is located and removed before the motor is put back into service. For such trouble hunting the apparatus needed is a lamp bank of sufficient resistance so that it can be safely thrown across the line, and an ammeter of capacity to carry the full load current of the motor at greatest torque.

The first step is to open the fuse-box door and fasten it open so that the operator can work freely. Try the lamp bank across each circuit on the motor side of the fuses to see whether any fuse is blown. If a blown fuse is found, it can, of course, be easily replaced, but do not put in a fuse of greater capacity than the current which the motor is supposed to carry.

If the lamps will not light on the motor side of the fuses, the question comes whether the break is in the fuse box or on the line side. Next test the fuse terminals on the line side of the box, and if the lamps light, the trouble is in the fuse box or in the motor circuits. If the lamps will not light on the line side of the box, trace back to the next fuses and cutouts and test there for open circuit in the same way.

If the fuses and the line are found o. k., remove a fuse and insert the lamp bank in its place; then close the motor switch and see if the lamps light. In like manner test each line to see in which the open circuit occurs.

If a break is found on the motor side of the fuse box, bare small spots on the leads at the motor and test across with the lamp bank to see whether the break is between the fuse box and the motor. If the motor leads are found o. k., the trouble is in the motor. Trouble in the motors leads is most likely to be in a switch or a

loose contact at one of the terminals. When testing at the motor, the motor switch must, of course, be closed, or no indication can be gotten.

Another set of tests is for grounds on the line which may divert current from the motor. To make this, try the lamp bank between a live contact and a dead ground such as a water pipe or steel beam of the building. If the lamps light, next remove all fuses from the box and close the motor switch; bridge the lamp bank from the top to the bottom of the box on each circuit to see on which line wire or phase of the motor the ground is. The switch, line and motor must then be gone over in detail to find where there is a break in the insulation. Even if an indication is not found, there may be a single ground, as two grounds are necessary to get a flow of current, but a single ground will not divert current from the motor, so is only harmful in that it may electrify some part of the apparatus so that a person touching it will receive a shock.

Bearings should be tested out occasionally for wear by inserting a thin steel wedge all around between the rotor and the stator. The wedge should go in the same distance at all points, for if the clearance is not equal, there will be an excess pull in the direction of the least clearance which will cause rapid wear, and also the clearance is so small that if it be reduced materially, the rotor will rub on the stator and cause heating. The remedy for worn bearings is rebabbiting or a new set of bearings.

If the circuits are found to be o. k., there is still the possibility of a short circuit in the motor windings, which may be in the end rings. If there it can usually be found by inspection, and will be by contact of the rings with the core of the rotor. If not found there, cut in the ammeter in each phase of the line, using a switch to short the ammeter while starting, if the starting current is above the capacity of the instrument. An old fuse shell with the leads soldered to the terminals makes a convenient device for this test. If one phase of the winding is shorted, the ammeter will show high current when connected in that phase and that winding must then be investigated.

If inspection shows that the trouble is where it can be got at easily, repair may be made on the spot, but it is generally better to send the motor to the shop where the repair can be more easily made and a thorough running test carried out to be sure that the motor is again in perfect condition.

Questions on Chapter XXIII

1. What are the advantages of the induction motor?
2. How is current supplied to the motor?
3. How does the rotor get current?
4. Why is the rotor spoken of as the secondary?
5. Which will give steadier torque, a 2-phase or a 3-phase motor?
6. Why do we speak of a squirrel-cage motor?
7. How many coils would a 6-pole, 3-phase motor have in the stator?
8. What would be the frequency in a rotor having 5 per cent slip, if line frequency is 60 cycles per second? (3.)
9. In a 6-pole motor with frequency 25 cycles per second and slip 3 per cent, what will be the r.p.m. of the rotor? (485.)
10. What will be the rotor e.m.f. of question 8 if the line voltage is 220? (11 v.)
    What for question 9? (6 v.)
11. Draw the connection diagram for a 3-phase motor having a starting switch, and auto-transformer connections for ⅓, ⅔ and full voltage.
12. Why is resistance thrown into the rotor circuits to increase starting torque?
13. Would a fan motor need rotor starting resistance? Why?
14. What is the objection to inserting rotor resistance to control speed?
15. Why do you test first on the line side of the fuse box when hunting for an open circuit?
16. Will a motor with one phase of the stator grounded tend to heat up?

CHAPTER XXIV

DIRECT-CURRENT AND ALTERNATING-CURRENT ELECTRIC MOTOR TESTS

For Insulation, Capacity, Efficiency, Temperature

INSTRUCTIONS given relative to the inspection of electric generators, Chapter VII, apply equally well to motors. If machine windings have been damaged or subjected to moisture, insulation resistance tests are advised. Measurements may be made by using 500-v. direct-current, and a 500-v. direct-current voltmeter,

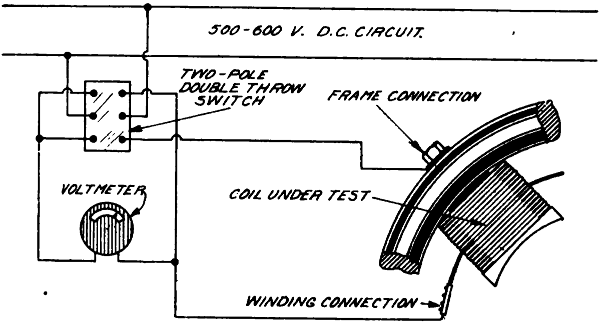


FIG. 179. DIAGRAM OF CONNECTIONS FOR INSULATION RESISTANCE TESTS

employing the scheme of connections indicated in Fig. 179. Read the line voltage, connect resistance to be measured in series with voltmeter, and take a second reading.

Dividing the product of the resistance of the voltmeter winding, in ohms, and the difference between line voltage and the voltage reading with insulation in series with voltmeter by one million times the voltage reading with insulation in series with voltmeter, will give as a quotient the resistance of insulation in megohms (one million ohms).

276 connect grounded
If inspection sho and the voltmeter be-
be got at eas side of circuit.
is general be approximately such
the repai of the rated current can
ning tes machine should have an insula-
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1.
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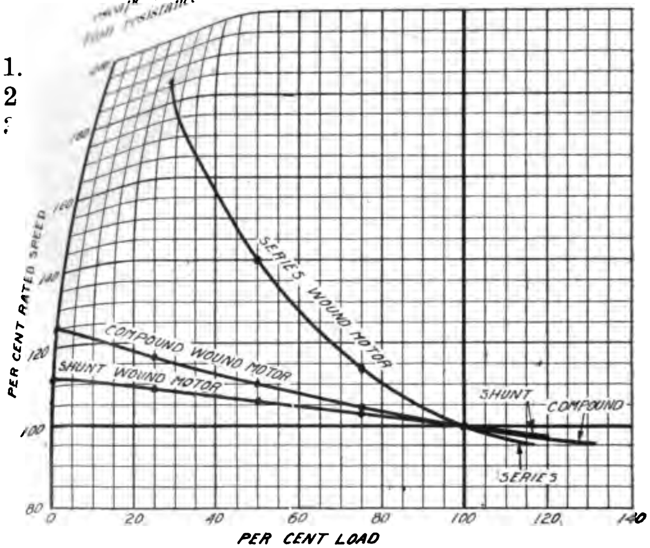


FIG. 180. TYPICAL DIRECT-CURRENT MOTOR SPEED CHARACTERISTICS

Motor speed tests may be conducted by measuring under loads ranging from zero to 150 or 200 per cent of machine rating, the number of revolutions per minute of the revolving member employing either some method of count, or some form of speed indicator. Curves obtained by plotting load values against corresponding speed values indicate the performance of the machine.

Due to increasing field strength, the speed of a series-wound motor will decrease with increasing load in the manner indicated in Fig. 180, while with a shunt-wound, direct-current machine, in which the field strength remains practically constant throughout a con-

siderable range of load, drop in speed from no load to full load seldom exceeds 5 per cent. Figure 180 also illustrates a typical compound-wound motor speed curve, the dropping of which may be accounted for by the effect of the increasing strength of the series field upon the constant field created by the shunt winding. In a differential compound-wound motor, the series winding

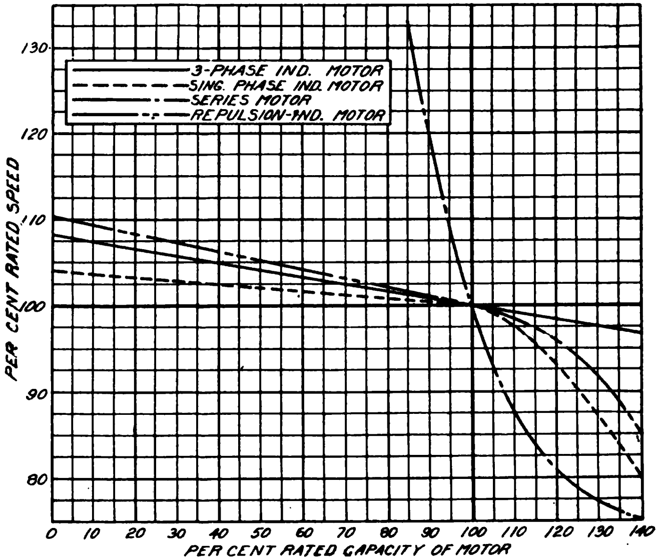


FIG. 181. TYPICAL ALTERNATING-CURRENT MOTOR SPEED CHARACTERISTICS

opposes the shunt winding and, as a consequence, the speed, if not remaining constant, increases with load.

Speed curves of various types of alternating-current motors are shown in Fig. 181. Throughout its rated capacity, the induction motor may be regarded as a constant speed machine, its change in speed from no load to rated load varying from 4 to 8 per cent, depending upon the capacity, the larger sizes usually having the better degree of regulation.

Efficiency

Efficiency of a machine is expressed as the ratio between the output and the input, the latter in the case of a motor being measured in the same manner as the output of a generator. Method of motor output measurement depends upon type of drive employed. If belted, the number of horsepower transmitted may be approximated by dividing the product of the velocity of the belt, in feet per minute, and the width of the belt,

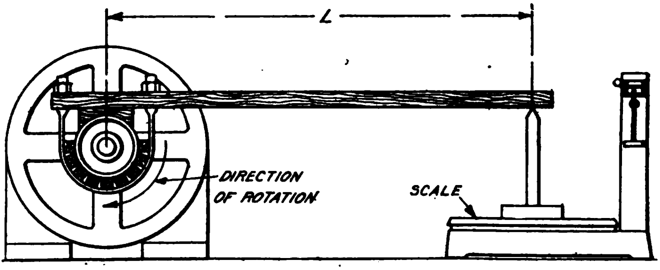


FIG. 182. ARRANGEMENT OF EQUIPMENT FOR A BRAKE TEST

in inches, by 550, while if direct drive is utilized, other means must be resorted to.

To measure electrical energy requirements under various load conditions, fit the motor shaft with a pulley having a diameter the same as the pitch diameter of the pinion or gear removed, and determine the number of horsepower developed by application of a Prony brake arranged in the manner indicated in Fig. 182. Adjust the load as desired and note speed of revolving member, in revolutions per minute, and reading of scale when in a state of balance. (The scale carries half the weight of the lever which must be subtracted from the scale reading to get the net reading.) Dividing the product of (horizontal distance L from center of shaft to point of application on scale platform, net scale reading in pounds, number of revolutions per minute of rotating member and 6 2832) by 33,000 will give number of horsepower developed.

Efficiencies of various types and sizes of direct and alternating-current motors are given in the tables, Figs. 183 and 184, respectively.

Curves and data furnished by motor manufacturers enable one to determine the efficiency of a motor at a given load. With machine running under normal voltage, measure current flow by means of an ammeter connected in the supply circuit and calculate per cent load being carried by multiplying by 100 the quotient ob-

Horsepower Capacity	Efficiency			Horsepower Capacity	Efficiency		
	1/2 Load	3/4 Load	Full Load		1/2 Load	3/4 Load	Full Load
7.5	77	81	82.5	135	89	90.5	91
15	82	85	86	165	90.5	91	91
20	82.5	86.5	86.5	200	90.5	91.3	91.5
25	84	86.5	87.5	265	91	91.5	92
35	85	88	89	400	91.3	91.8	92
45	87	89	89.5	500	91.8	92.3	92.5
65	88	89.5	90.5	650	91.8	92.2	92.5
80	88.5	90.5	91	1000	92	92.3	92.5
100	88.5	90.5	91	1250	92.5	93	93.5
120	88.5	90.5	91				

FIG. 183. EFFICIENCIES OF VARIOUS TYPES AND SIZES OF DIRECT-CURRENT MOTORS

Horse-power Rating	Number of Poles	Single Phase				Polyphase			
		1/2 Load	3/4 Load	Full Load	5/4 Load	1/2 Load	3/4 Load	Full Load	5/4 Load
1	4	60	63	68	62	74	78	79	79
2	4	71	75	78	77	77	81	82	82
5	4	71	76	77	76	82	84	85	84
10	6	75	79	80	79	84	85	85	83
20	6	85	88	86	85	85	87	87	86
30	8	77	81	83	82	87	89	88	87
50	8	82	84	86	86	87	89	90	90
75	10	--	--	--	--	88	90	90	89
100	10	--	--	--	--	88	90	90	90
150	10	--	--	--	--	88	90	91	90

FIG. 184. EFFICIENCIES OF VARIOUS TYPES AND SIZES OF ALTERNATING-CURRENT MOTORS

tained by dividing the ammeter reading by full load rated ampere capacity of the motor as given on the name plate. Reference to manufacturer's curve will give corresponding efficiency.

Tests of this nature are preferably made under maximum load conditions, and if found that the motor is not operating for the greater part of the time under highest degree of efficiency obtainable, a machine of different size should be substituted in the case of individual drive or rearrangement of driven machines made where group drive is employed. Make only such changes as will insure working the motor under a load which corresponds as nearly as possible to maximum efficiency.

CAPACITY

WHERE motors are required to carry momentary heavy overloads, but otherwise are running considerably underloaded and at exceedingly low efficiency, and in the case of alternating-current induction motors at low power factor, smaller machines equipped with sufficiently heavy flywheels may often be used to advantage. Under such conditions, employ a motor of such size as will most readily carry the average load. The size needed may be obtained from the records of a recording ammeter connected in series with the machine, although where such an instrument is not available, the same result may be secured approximately, by the average of a series of indicating ammeter readings taken every minute over a given period of time.

Where new machines or groups are being installed, marked savings may be realized by determining the actual requirements before purchasing the driving motor. Temporarily install a motor of size sufficient to operate the machine or group under test, determine the actual power requirements from instruments connected in the supply circuit in the manner indicated above. From the results obtained (in watts) subtract the losses occurring within the motor at the average load under which it operates and divide the difference in watts by 746 to obtain the number of horsepower necessary to drive the machine or the group as the case may be.

The motor used for this purpose may be temporarily installed at the point where it is desired to place the regular machine or, as in the case of large installations where frequent changes are made in load and arrangement of driven machines and a motor is kept in stock

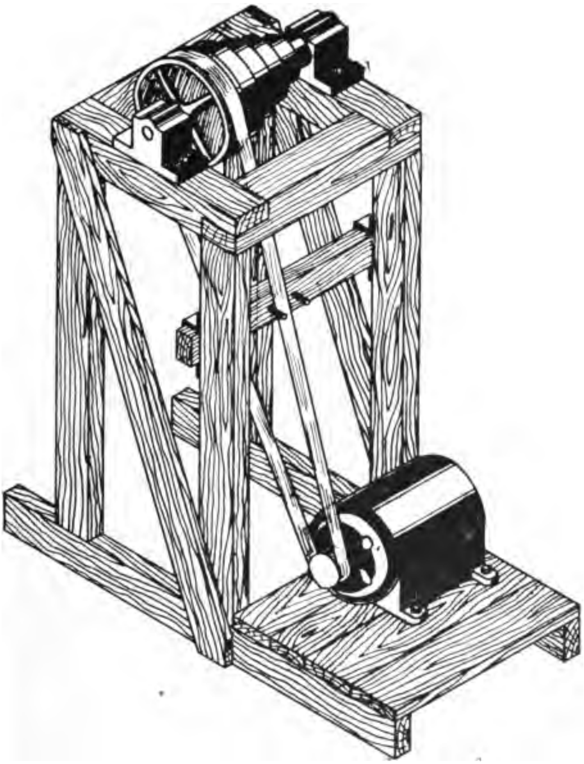


FIG. 185. CONSTRUCTION OF TEST MOTOR RACK FITTED WITH CONE PULLEY

for such test purposes only, the mounting shown in Fig. 185 may be utilized to good advantage, equipping the apparatus with a counter shaft and a set of cone pulleys so as to have available a comparatively large range of speeds.

A scheme of electrical connections, particularly convenient for checking up motors already in place, is illus-

trated at A and B, Fig. 186. In the case of a direct-current or a single-phase alternating motor, a "blown" fuse fitted with dummy connectors tied in with the ammeter or the current coil of the wattmeter is used instead of the regular fuse, thus eliminating the necessity of interfering with any permanent connections. With a three-phase machine, two of these dummy fuses will

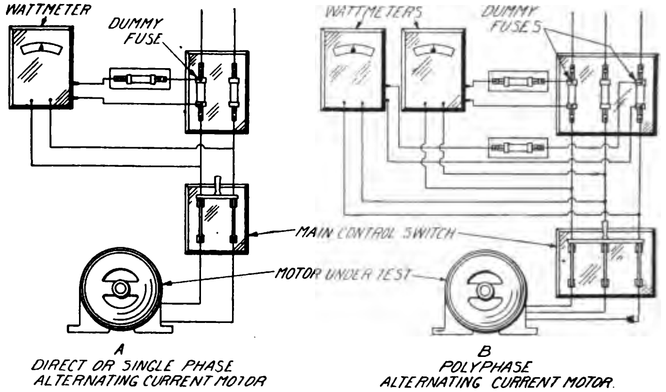


FIG. 186. DIAGRAMS OF CONNECTIONS FOR CHECKING UP MOTOR LOADS

have to be used, and in either case, in order to protect the machine under test fully, the circuit leading to the measuring instrument should be fitted with a portable fuse of capacity equal to that removed from the fuse block.

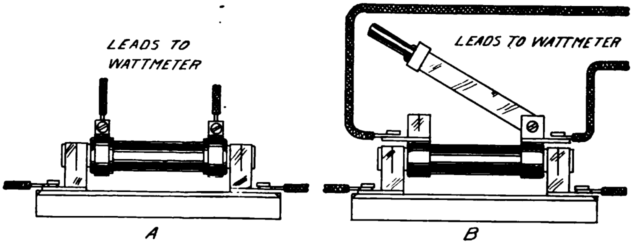


FIG. 187. METHODS OF CONNECTING DUMMY FUSES AS EMPLOYED IN FIG. 186

A single-pole knife switch mounted on the dummy fuse in the manner shown in Fig. 187B will allow cutting out the ammeter or the current coil of the wattmeter without interfering with the operation of the motor.

Starting Requirements

Power required to start a machine or group of machines may, in the case of belt drive, be determined by

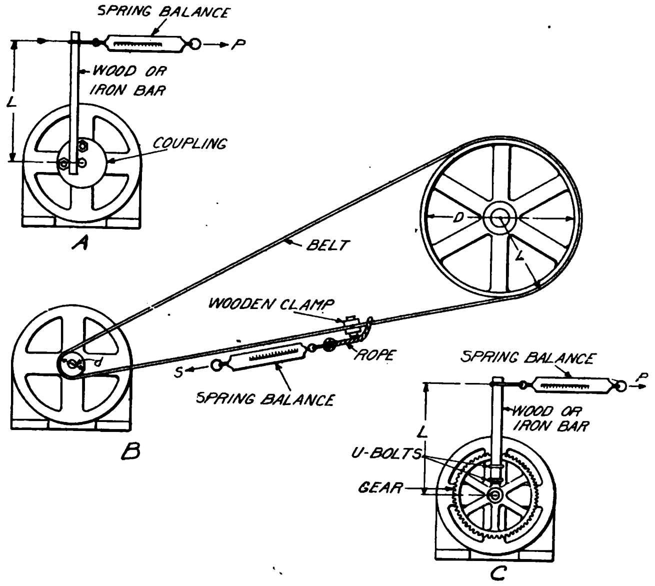


FIG. 188. METHODS EMPLOYED TO MEASURE MOTOR TORQUE

measurement of the torque in the manner indicated in Fig. 188, B. With a spring scale attached to the belt by means of a wooden clamp and held parallel to the belt, apply force to the scale to turn the driven pulley a small part of a revolution, and note the scale reading. This is the force in pounds required to start the load at a radius of L ft.; the torque in pounds-feet is equal to the product of this force in pounds and L in feet, while the value of the number of horsepower required is equal to the quotient obtained by dividing the product of (the

torque in pounds-feet and the speed of the driven pulley in number of revolutions per minute) by 5252.

Where a direct-connecting coupling is employed, the scheme indicated at A, Fig. 188, may be utilized, while if the motor shaft is fitted with a gear, the scale may be attached directly to one of the arms of the gear as at C, Fig. 188, to determine the pull required to start the load.

Slip Tests

Induction motors may be tested for slip by attaching to the shaft of the machine a black disk with p white radial lines or sectors painted upon it, where p is the number of poles of the motor. If, with the motor running, the disk is illuminated by means of an alternating-current arc lamp connected to the same lines as the motor, synchronism is indicated by the stationary appearance of the white lines on the disk. If, however, the motor is below synchronism, the disk will appear to rotate at a speed equal to the difference between the synchronous and the actual speed. Dividing the number of revolutions at which the disk seems to rotate by the synchronous speed of the machine, and multiplying the quotient obtained by 100 will give, as a result, the per cent slip.

In a reasonably good motor the per cent slip should not be in excess of 12.

Predetermining Performance of Induction Motors

With the aid of the total no load watts, W_0; the no-load amperes, i_0 (per phase); the total (short circuit) watts, W_s, with rotor blocked, and the total short circuit current i_s (per phase) all at rated machine voltage E, a circle diagram may be constructed by means of which the performance of a polyphase induction motor may be predetermined.

As indicated in Fig. 189, lay out on suitable co-ordinate paper axis OE and OX, the former representing the value of the impressed electromotive force. To a convenient scale take OP equal to 100 per cent power factor and subdivide as shown. With OP as a radius describe

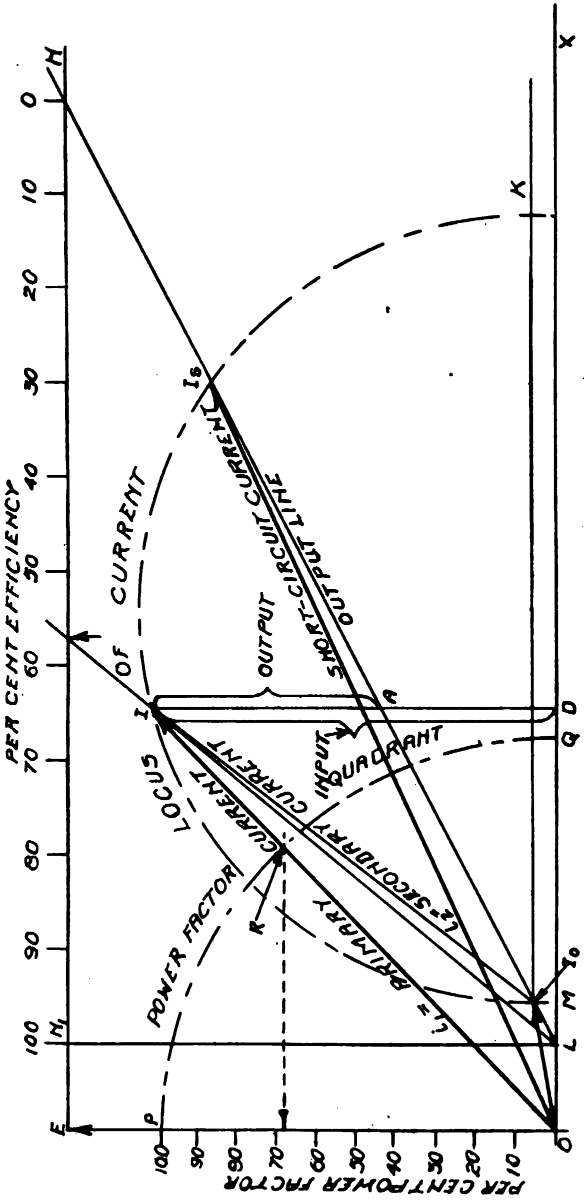


FIG. 189. TYPICAL CIRCLE DIAGRAM FOR PREDETERMINATION OF INDUCTION MOTOR PERFORMANCE

quadrant PRQ, the point of intersection of which with the primary current vector when extended horizontally to the vertical scale OP gives the power factor reading corresponding to the location of the primary current vector.

t Initial temperature, Centigrade	a Temperature coefficient	t Initial temperature, Centigrade	a Temperature coefficient
0	0.00420	26	0.00379
1	0.00418	27	0.00377
2	0.00417	28	0.00376
3	0.00415	29	0.00374
4	0.00413	30	0.00373
5	0.00411	31	0.00372
6	0.00410	32	0.00370
7	0.00408	33	0.00369
8	0.00406	34	0.00368
9	0.00405	35	0.00366
10	0.00403	36	0.00365
11	0.00402	37	0.00364
12	0.00400	38	0.00362
13	0.00398	39	0.00361
14	0.00397	40	0.00360
15	0.00395	41	0.00358
16	0.00394	42	0.00357
17	0.00392	43	0.00356
18	0.00391	44	0.00355
19	0.00389	45	0.00353
20	0.00388	46	0.00352
21	0.00386	47	0.00351
22	0.00385	48	0.00350
23	0.00383	49	0.00348
24	0.00382	50	0.00347
25	0.00381		

FIG. 190. TABLE OF TEMPERATURE COEFFICIENTS FOR USE IN CALCULATING MACHINE TEMPERATURE RISE

With rotor blocked, apparent horsepower input is equal to the quotient obtained by dividing $\sqrt{3}\ i_s\ E$ by 746. Plot this value as vector OI_s, the angle with OE being dependent upon the power factor determined by dividing 100 W_s by $\sqrt{3}\ i_s\ E$.

OI_0 represents apparent horsepower input at no load and is equal to $\sqrt{3}\ i_0\ E$ divided by 746, the power factor being obtained by dividing 100 W_0 by $\sqrt{3}\ i_0\ E$.

Draw I_0 M the power component; O M is the wattless component.

Through I_0 and parallel to OX draw I_0K, using this as a base for the semi-circle drawn through points I_0 and I_s and representing the locus of the end of the horsepower vector as the load on the motor increases. Vector OI drawn for a given load will represent the apparent horsepower input, while ID measures to the same scale the true horsepower input.

OI may also represent the value of the primary current, and is reducible to this by dividing 746 OI by E $\sqrt{3}$.

Joining I_0 and I_s will give the output as represented by IA, thus rendering it possible to determine the efficiency by dividing IA by ID, although this may be obtained more directly by construction of the efficiency scale. Produce I_0 I_s to L and erect at that point perpendicular LN_1, N_1, at such a distance from OX as will allow the ready division of NN_1, into 100 equal parts.

To determine per cent efficiency corresponding to input ID, draw LI extended to the efficiency scale, the point of intersection giving the per cent efficiency.

The power factor for any given value of primary current as OI may be obtained by projecting horizontally to the power factor scale the point of intersection of OI with quadrant PRQ.

Temperature Determinations

Machine temperatures may be obtained by means of thermometers applied to the hottest accessible part, by increase of winding resistance and by the imbedded temperature-detector method. With thermometers the actual temperature is estimated by adding to the highest observed reading a correction factor of 15 deg. C., except where the instrument is applied directly to the surface of a bare winding in which case but 5 deg. C. is added.

In employing the measurement of resistance method, temperature rise in degrees Centigrade is obtained by dividing the difference between the resistance of the windings before test and their resistance at time of shutdown, by the product of the resistance at time of

shutdown and the temperature coefficient, the value of which may be obtained by reference to the table shown in Fig. 190. For ordinary purposes, an initial temperature of 25 deg. C. (77 deg. F.) may be assumed, in which event a temperature coefficient of 0.003,81 is used.

In the case of two-layer windings having thermocouples between coils and between coil and slot, add 5 deg. C. to the highest reading. In single-layer windings with detectors between coil and core, and between coil and wedge, add to the highest reading 10 deg. C., plus 1 deg. C. for each 1000 v. above 5000 v. terminal pressure.

Questions on Chapter XXIV

1. Why does a series motor slow down under load?
2. What is the minimum insulation resistance for a motor?
3. How is insulation resistance measured?
4. What would be the insulation resistance of a motor which gave on test the following readings: Line e.m.f., 550; reading of voltmeter in series with insulation, 5 v.; voltmeter resistance, 10,000 ohms? (1.09 megohms.)
5. If a motor on test shows an ammeter reading of 25 and line voltage is 220, what is the horsepower input? (7.36 hp.)
6. If the brake test of the motor in question 5 gave readings as follows: Speed, 1500 r.p.m.; arm L, 3 ft.; weight of arm, 8 lb.; scale reading, 11.25 lb., what is the horsepower output? (6.21 hp.) What is the efficiency? (0.838 = 83.8 per cent.)
7. In a test run, a 45-hp. motor showed ampere readings of 100, 160, 150, 175, 195 on a 110-v. circuit. Using the efficiency from Fig. 183, what size motor should be installed? (Av. input, 22.65 hp. Av. output, 19.8 hp.)
8. If the test of Fig. 188 shows a spring balance reading of 50 lb. on an arm of 3 ft., what starting torque must the motor have? (150 lb. ft.)
9. What horsepower motor will be needed if the speed is 1000 r.p.m.? (28.27 hp.)

10. In an alterating-current motor test, the no load current is 15 amp, e.m.f. 550 v. and watts 7450; the short circuit current is 110 amp. and watts 51,500. What is the apparent horsepower at no load, and on short circuit? (11.05; 81.)
11. What is the angle of lag for each case? (25 deg. 15 min.; 31 deg. 35 min.)
12. Lay out the diagram like Fig. 189 and find the wattless power for no load. (3750 w.)
13. Complete the diagram and find the actual output when the primary current is 80 amp., and the actual input in watts. (16,000 w.; 32,500 w.)
14. What is the efficiency? The power factor? (49 per cent; 0.75.)

CHAPTER XXV

PHASE ADVANCERS

Correction of Low Power Factor of Induction Motors

GREAT growth in the use of the induction motor in recent years has resulted in a real need for improvement in the power factor of supply systems. The importance of a good power factor is generally recognized to keep down line losses, increase the useful output of generators and reduce their cost. As early as 1891, the idea of using paper condensers for providing idle leading current to compensate the idle lagging-current systems, was proposed. As no real progress was made along these lines toward practical applications, and conditions then changed, the subject was dropped. Today, the most commonly used method for the correction of power factor of a system is the employment of over-excited synchronous motors, converters or synchronous condensers. Now, there has been placed on the market a new type of machine, called the phase advancer, which is applied to the individual induction motor and has many advantages over other power factor correction methods.

In the synchronous motor, the magnetizing field is produced by a rotating magnet excited by continuous current. By supplying more continuous ampere-turns than are necessary to produce the normal magnetic field in any particular machine, it is possible to create in the system a leading current, which will compensate for a lagging current in another part of the system and produce a power factor of unity, or even a leading current.

The phase advancer stands in the same relation to an induction motor as an exciter does to a synchronous motor. For the induction motor, however, continuous current cannot be used for the magnetizing currents in the secondary because the motor slips under load. The magnetizing current must be polyphase of low frequency

which corresponds in each instance to the slip of the induction motor.

Construction of Advancer

The phase advancer consists of a continuous current drum armature with a commutator having three brush studs per pair of poles, displaced relative to one another by 120 electrical degrees. The stator consists of a frame with the laminations assembled, but having no poles or windings, as shown in Fig. 191.

FIG. 191. TYPICAL PHASE ADVANCER

The phase advancer is direct connected to a small squirrel-cage, constant-speed, induction motor. The only driving power required is that to supply the friction, windage and hysteresis losses and is, therefore, comparatively small, i e., about 1 hp. for a 600-hp., 2000-volt induction motor. The copper losses are provided by the main induction motor rotor.

In Fig. 192 is illustrated a simple scheme of connections where A is the induction motor; B, the phase advancer, direct connected to its driving motor, C; D, a standard controller and resistance for starting; E, a 2-pole, single-throw, short-circuiting switch; and F, a transformer and fuses. The switch, E, is used to short-circuit the phase advancer when starting the induction motor, A, which is accomplised in the usual way by the drum controller. Motor C is started, and after the motor A is up to speed, the switch, E, is opened.

Consider, for the moment, that the phase advancer is standing still and is receiving current at slip frequency from the slip rings of the induction motor. The phase advancer under these conditions acts as a 3-phase choke coil, the current producing a field which

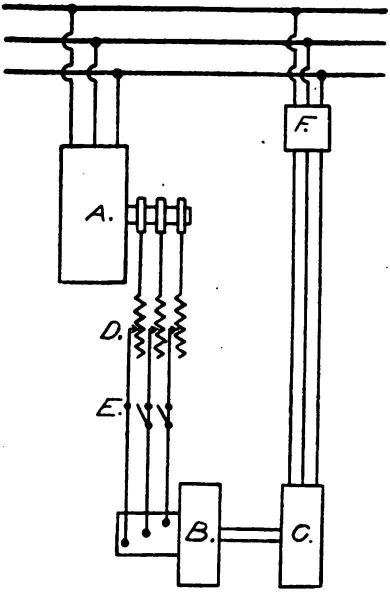
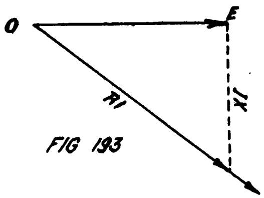


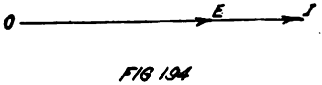
FIG. 192. DIAGRAM OF CONNECTIONS FOR APPLYING A ROTARY PHASE ADVANCER TO AN INDUCTION MOTOR

revolves in space at a speed corresponding to the frequency of the current supplied to the brushes.

In Figs. 193-195, we have three vector or clock diagrams in which the hands are considered rotating in a counter-clock-wise direction. Figure 193 shows the phase e.m.f., E, at the brushes and the current, I, fed to each brush in which RI is the voltage component used to overcome the resistance and XI is the component used to overcome the e.m.f. produced by the revolving field; i.e., the e.m.f. of self-induction. This figure is typical of any representing an alternating current lagging behind the applied e.m.f.

When the armature is driven in the direction in which the field revolves and at a speed corresponding with the speed of the field, the relative motion of the field and the armature becomes zero; this is equivalent to the disappearance of the self-inductive effect, as indicated in Fig. 194, and results in the current being in phase with the e.m.f., or OE coincides with OI.





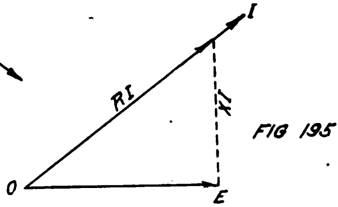


FIG. 193. VECTOR DIAGRAM, SHOWING CURRENT LAGGING BEHIND LINE VOLTAGE

FIG. 194. VECTOR DIAGRAM, SHOWING CURRENT IN PHASE WITH LINE VOLTAGE

FIG. 195. VECTOR DIAGRAM, SHOWING CURRENT LEADING LINE VOLTAGE

If, however, the armature is driven at a speed greater than the speed of the field, the XI component of Fig. 193 is reversed in sign and E assumes a position, as shown in Fig. 195; that is, the current will lead the e.m.f. This negative reactance e.m.f. in series with the rotor circuit of an induction motor is able to neutralize the reaction of the induction motor, which formerly pushed the primary current into a lagging phase. It is in this way that the condenser effect is produced and the power factor improved.

Benefits to Be Derived by Its Use

The phase advancer can be applied to any induction motor having a wound rotor and slip rings and can be designed to correct the power factor to unity from

about ¼ to 1½ normal load. A new motor designed to work with an advancer can be made considerably smaller than one not using the advancer, due to the fact that it is cheaper to use a slightly greater amount of iron and considerably less copper in the construction of the motor. This, however, will naturally result in a cheaper machine and a worse power factor. This defect is, then, readily corrected by the phase advancer. The saving in the cost of the motor will compensate for

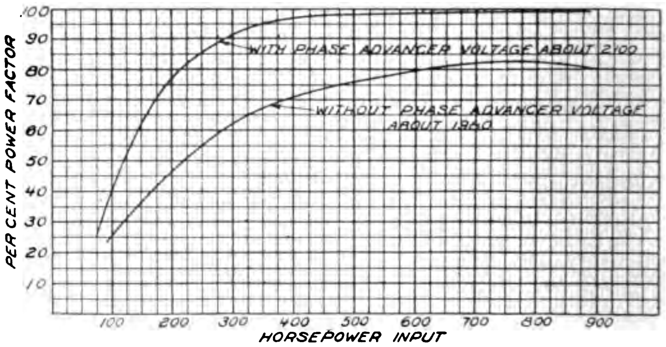


FIG. 196. THE LOWER CURVE SHOWS THE POWER FACTOR OF A 600-HP. INDUCTION MOTOR WHEN RUN WITHOUT A PHASE ADVANCER. THE UPPER CURVE SHOWS THE POWER FACTOR OF THE SAME MOTOR WITH THE PHASE ADVANCER IN CIRCUIT.

the cost of the advancer. If a high power factor is desired, it is cheaper to build an iron machine with a phase advancer than a copper machine without any.

A smaller motor has smaller losses, so that the power to drive the smaller motor and phase advancer would in most cases be less than that required to drive a large motor without the phase advancer. By the application of a suitable phase advancer, the output of an old motor may be increased from 20 to 30 per cent and its power factor improved at the same time.

If the induction motor is not to be run continuously and in one direction the greater part of the time, the phase advancer cannot be used. Its most important

application is to large, slow-speed motors which have an inherently poor power factor and to motors which run most of the time at part load and therefore at poor power factor.

Figure 196 shows a curve illustrating the effects of a phase advancer on a 600-hp. induction motor. The upper curve shows the power factor of the motor when run with a phase advancer and the lower curve, the power factor when run without the advancer.

Questions on Chapter XXV

1. What causes low power factor in an induction motor?
2. What windings are used on the phase advancer?
3. What per cent of the power of the induction motor is needed to drive the phase advancer? (0.167 per cent.)
4. With what style of motor can the phase advancer be used? Could it be adapted to a squirrel-cage type?
5. What effect does added iron have on the power factor of an induction motor? On the cost?
6. Would you use a phase advancer with a crane motor?
7. What per cent saving in line loss would you expect by using a phase advancer with a motor running at half load? (About 30 per cent.)

CHAPTER XXVI

THE ROTARY CONVERTER

VOLTAGE AND CURRENT RELATIONS; CONTROL OF DIRECT-CURRENT VOLTAGE; EXCITATION; RATING; OPERATION

WITH the introduction and employment of high-tension alternating currents has come the extended use of the rotary converter for the transformation of these alternating currents to direct currents with an accompanying stepping down of voltage. Rotary converters find their greatest field of usefulness in substations, receiving energy from high-tension transmission lines and supplying low-voltage direct current for electric railway and lighting service, in the electrochemical and metallurgical industries, and are to some extent used to convert direct current to alternating current, in which case they are known as inverted converters. Inverted converters are generally found in industrial establishments where direct current is the only available source of energy and where some alternating-current apparatus, such as motors and lamps, is installed.

While to some extent possessing the characteristics of both alternating and direct-current machines, a rotary converter will, in many respects, be found to differ materially in its general makeup and mode of operation from its component parts.

In the actual motor and generator actions in the machine, the heating effect of the armature current and the magnetizing action of the armature current, the machine is essentially unlike a sychronous motor and essentially unlike a direct-current generator.

GENERAL THEORY OF CONVERTERS

AS AN ILLUSTRATION of the general workings of a rotary converter and as explained by Franklin and Estey in their Elements of Electrical Engineering let us consider an ordinary 4-pole direct-current generator having a ring-wound armature, commutator and brushes. If,

then, such a machine is provided with two collector rings placed adjacent to the commutator or other convenient place on the shaft and each ring, as shown in Fig. 197, connected to the commutator at diametrically opposite points, connections for the two rings being at 90 deg. apart, it will be possible to drive this machine from some external source and take direct current from those brushes in contact with the commutator, and alternating

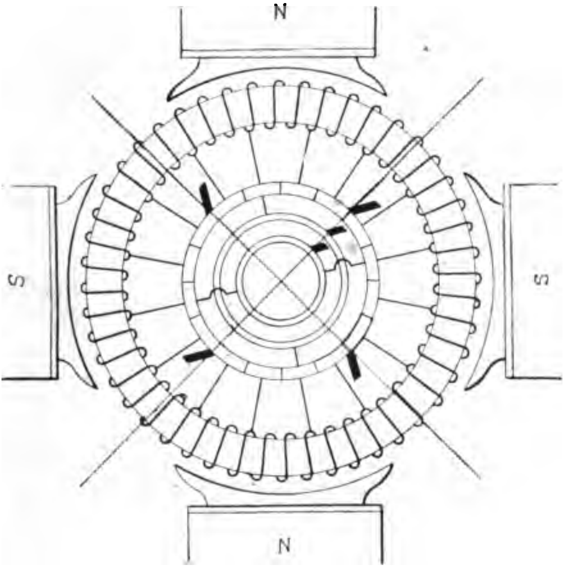


FIG. 197. DIAGRAM OF ARMATURE CONNECTIONS OF A 4-POLE, 2-RING ROTARY CONVERTER

current from those brushes in contact with the collector rings; it may also be driven as a direct-current motor and deliver mechanical power, or alternating current or both; or it may be driven as a synchronous alternating-current motor and deliver mechanical power, or direct current or both.

A machine like this, having two collector rings, is called a 2-ring or single-phase converter. A 4-pole, 3-ring or 3-phase converter is ordinarily provided with 3 collector rings connected to commutator bars 60 deg. apart, while the 4-ring or 2-phase converter, also of the

4-pole type, has 4 collector rings connected to commutator bars 45 deg. apart.

Letting the number of collector rings on a given converter, having a simple lap armature winding, be represented by the letter n, we find in an n ring converter that ring 1 is connected to all the commutator bars which for a given armature position lie midway between the north poles of the field magnet. Further, letting l be the number of bars between commutator bars of this set, ring 2 will be connected at points l/n bars ahead of the first set, ring 3, $2l/n$ bars ahead of the first set, ring 4, $3l/n$ ahead of the first set, etc.

As an example, let us consider a 6-pole machine having 72 commutator bars to be made into a 3-ring converter. In this case, n or the number of collector rings is equal to 3. Ring 1 will then for a given position of the armature be connected to all commutator bars lying midway between the north poles of the field magnet, requiring 3 taps from the ring to the commutator and as these must be equidistantly placed, this ring will be connected to bars 1, 25 and 49. In this case, l is equal to 24, so that according to the above statement, it will be necessary to connect ring 2 to those bars l/n ahead of the first set; i.e., ⅓ of 24, or 8 bars ahead, thus connecting ring 2 to bars 9, 33 and 57, and in a like manner ring 3 would be connected to bars 17, 41 and 65.

Voltage Relations

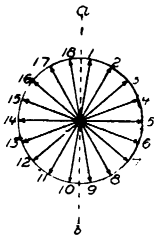
From the theory of alternating currents, we know that in the case of a true sine wave of alternating electromotive force, the value of the maximum electromotive force is $\sqrt{2}$ or 1.4 times that of the effective e.m.f.

Let E be the value of the steady electromotive force between the direct-current brushes of a 2-ring converter and E_2 the effective value of the alternating electromotive force between the collector rings of that machine. The maximum value of the alternating electromotive force between the collector rings of such a converter occurs at the instant the commutator bars to which the collector rings are connected come in contact with the direct-current brushes. This maximum value of the

alternating-current electromotive force is then equal to E. Then from the above we can readily see that the effective value of the electromotive force between the collecting ring brushes is equal to the maximum electromotive force or E divided by $\sqrt{2}$, or $E/1.4$.

The relation existing between the electromotive forces for not only a 2-ring but any n-ring converter may conveniently be shown graphically.

Assume, in Fig. 198, that each of the various radii or vectors represent those electromotive forces induced in the respective conductors of a rotary converter armature as it revolves. While the value of the induced



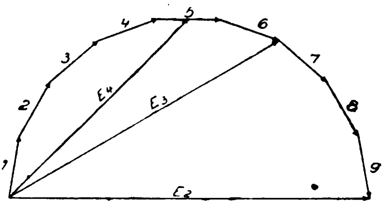


FIG. 198. VECTOR DIAGRAM OF ELECTROMOTIVE FORCES INDUCED IN ARMATURE CONDUCTORS

FIG. 199. ELECTROMOTIVE FORCE DIAGRAM CONSTRUCTED BY MEANS OF VECTORS SHOWN IN FIG. 199

electromotive force in any conductor is the same as that in any adjacent conductor, it is, however, ahead or behind in phase that electromotive force in the adjoining conductor by an amount equal to $360/N$, where N is the number of conductors. In the case of an armature having 18 conductors, the electromotive force vectors of which are shown in Fig. 198, we find the various conductors spaced at distances of 360/18, or 20 deg., so that the electromotive forces induced in the various adjacent conductors are out of phase by that amount.

The value of the electromotive force across the brushes of a 2-pole, 2-ring converter, the rings of which are connected to opposite commutator bars, is equal to the vector sum of the electromotive forces induced in the conductors lying between these taps, or the sum of

the electromotive forces induced in those conductors distributed throughout an angle of 180 deg. With a little study, the method of constructing the diagram in Fig. 199 will be readily understood. Consider those vectors only which lie on the right of dividing line *ab*, and which are numbered 1 to 9, inclusive. Transferring them as shown, employing the same lengths and relative directions as in Fig. 198, we obtain the polygon having sides, 1, 2, 3, 4, 5, 6, 7, 8, 9 and E_2. We therefore find that the value of the electromotive force between the rings of a 2-ring converter is equal to the chord E_2 of Fig. 199, subtending an angle of 180 deg.

Type of Converter	Actual ratio of voltage across rings to voltage across direct-current brushes	
	No Load	Full Load
2-Ring	0.715	0.725
3-Ring	0.610	0.620

FIG. 200. VOLTAGE ACROSS RINGS OF ROTARY CONVERTER

In a similar manner, the value of the electromotive force across any two rings of a 3-ring converter, the rings of which are connected to the armature windings at points 120 electrical degrees apart, is represented by E_3, that chord of the polygon subtending an angle of 120 deg., and the effective electromotive force between any two rings connected to the armature windings at points 90 electrical degrees apart may be represented by that chord E_4 of the polygon which subtends an angle of 90 deg.

Further investigation of this phase of the subject is needless, as the theoretical ratios of alternating to direct-current voltage are not always found to hold good in practice. This is due to various causes, chief among which are the deviation of the generator voltage from a true sine wave, the voltage drop in the armature windings, the position of the direct-current brushes on the commutator and the degree of field excitation.

When the alternating electromotive force of supply is approximately harmonic, when the pole faces of the converter cover ¾ of the armature surface, and when the direct-current brushes are in a neutral position, the

voltage ratios are approximately as in the table of Fig. 200. This table does not, however, include the voltage ratio values of the 4 and 6-ring machines, because the alternating voltage of a 4-ring converter is usually specified as the effective voltage between opposite rings, which is the same as that of a 2-ring machine. The alternating voltage of a 6-ring converter is usually specified either as the voltage between opposite rings, in which case it is the same as that of a 2-ring converter or the voltage between every other ring, in which case it is the same as that of a 3-ring converter.

Control of Direct-Current Voltage

In any given converter a practically fixed ratio exists between the alternating electromotive force and the direct-current electromotive force, so that unless means are provided to produce the contrary, the direct-current electromotive force will rise and fall with the applied alternating electromotive force. In order, therefore, to vary the voltage of the direct-current side of a converter, it is necessary to vary the alternating-current voltage supplied to the collector rings. This control of direct-current voltage may be obtained by means of several methods such as, (a) variable ratio transformers, (b) induction regulators, (c) synchronous regulators or boosters, (d) direct-current boosters, or (e) compounding.

Variable Ratio Transformers

For this method of voltage variation, ordinary potential transformers are interposed between the supply lines and the machine. The secondaries of these transformers are provided with taps connected to a special switch or controller, so that by using different taps, the voltage between collector rings may be varied to suit the direct-current side requirements.

Induction Regulators

These used in connection with rotary converters are similar to the regulators employed to raise or lower the voltage of single-phase light and power circuits, and consist of a primary winding of comparatively fine wire

connected across the line wires and a secondary winding in series with the load. By varying the relative positions of these 2 windings, a voltage "boost" or "buck" is readily obtained.

Synchronous Boosters

One of the most widely employed methods of rotary converter voltage control is the use of synchronous regulators or boosters. These are merely small alternating-current generators having the same number of field poles as the converter, and generally direct connected to the converter and driven by it. The revolving armature of the booster is connected in series with the armature and collector rings of the converter, and the field magnets are separately excited.

As the intensity of the booster field is increased, the voltage induced in the armature windings is correspondingly increased and added to the line voltage, thus raising not only the voltage supplied to the converter armature, but also that across the direct-current brushes. In some machines found in practice, the excitation and polarity of the booster may be reversed, so that the booster voltage may be subtracted from the normal value of the impressed alternating voltage and a corresponding reduction of direct-current voltage obtained. This method then gives the same results, although to a somewhat greater extent, as the induction regulator.

Direct Current Booster

No attempt is made to control either the voltage supplied the collector rings or that delivered across the direct-current brushes, in this scheme of voltage control. A low-voltage direct-current generator or booster is connected in series with the direct-current line and by varying the voltage generated by this booster, which is added to that delivered by the converter, the line voltage may be varied to meet requirements.

Compounding

If, under normal conditions, a converter is excited so as to give an electromotive force less than that of the supply lines, the machine will, when running at a

speed corresponding with the frequency of the system, draw a lagging current which tends to strengthen the converter field so that the generated electromotive force of the alternating side is made equal to that of the system. In a similar manner, if the field be over-excited, the current taken from the supply lines will be leading and will tend to demagnetize the fields sufficiently to make the alternating electromotive force again equal to that of the system.

Connecting inductive reactances in the supply lines will, with a lagging current, cause a voltage drop and with a leading current a voltage rise, so that, by under-exciting the converter field the voltage applied to the collector rings will be less than that of the supply lines, while an over-excited field will draw a leading current resulting in a voltage across the collector rings higher than that of the line. The change in phase between the electromotive force and the current delivered to the converter is due to the degree of excitation which is, in turn, regulated by the load current; the greater this is, the greater will be the excitation which, in turn, will draw a greater leading line current, resulting in a higher applied electromotive force. With the inductive reactance, the effect of the series coils on the field of a rotary converter is not unlike that produced by compounding a direct current generator.

In many instances, it is found that the inductance possessed by the transmission lines and converter circuits—that is, the series windings—is sufficient to produce the desired result so that no additional inductance is necessary.

Regulating Pole Converter

This type of machine is claimed by its manufacturers to offer the simplest method of obtaining a variable direct-current voltage from a constant alternating-current voltage and differs from a standard machine only in that the pole structure is divided into two or more parts—a main pole and regulating poles. With constant impressed alternating electromotive force the direct-current voltage is changed by varying the excitation of

the regulating poles, the only auxiliary apparatus required being a field rheostat for varying the regulating-field current.

Field Excitation

Rotary converter fields may be excited by armature reaction, by direct current taken from the commutator of the machine or by use of an auxiliary direct-current generator. Of these methods, the last two named are most generally employed in practice.

Armature Reaction Excitation

This method is used to but a limited extent. When a synchronous motor or rotary converter draws a lagging line current, the magnetizing action of this current in the motor armature strengthens the field magnetism of the machine to such an extent that no outside source of excitation is required.

Self Excitation

This method is similar to that used in the ordinary direct-current generator, and is brought about by the employment of series, shunt or compound windings. When employing only the series windings, zero excitation accompanies zero load, while full-rated excitation is obtained with full-load direct-current output, a scheme not well suited for rotary converter work.

The shunt scheme gives an approximately constant field excitation and is extensively used. By inserting an adjustable rheostat in series with the shunt winding, the excitation may be varied for the purpose of controlling the power factor of the converter.

Compound excitation provides for slightly increased field excitation with increased direct-current output. Its use is limited, however, for the reason that too great an increase of field excitation results in the converter falling out of synchronism and stopping.

Separate Excitation

With this scheme, separate direct-current exciters are used which may either be direct-connected to the

converter or separately driven by a motor, engine or turbine.

Questions on Chapter XXVI

1. What are the uses of the rotary converter?
2. At what points in an 8-pole machine with 96 commutator bars would the rings of a 2-ring converter be connected? (No. 1 to bars 1, 25, 49, 73; No. 2 to bars 13, 37, 61, 85.)
3. What would be the connections for the above machine for a 6-ring converter? (No. 1 to bars 1, 25, 49, 73; No. 2 to bars 5, 29, 53, 77; No. 3 to bars 9, 33, 57, 81; No. 4 to bars 13, 37, 61, 85; No. 5 to bars 17, 41, 65, 89; No. 6 to bars 21, 45, 69, 93.)
4. If the d.c. voltage of a rotary converter is to be 220 volts, what a.c. voltage would be needed for the 3-ring type? (136.4 v.)
5. How is the d.c. voltage of a converter controlled from the supply? From the d.c. side? From the excitation?
6. What is the effect of too great a field excitation?

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